AN ECONOMIC ASSESSMENT OF ON-FARM SURFACE WATER RETENTION SYSTEMS

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By

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ABSTRACT

Regions dependent on agricultural production are concerned about the uncertainty associated with climate change. Extreme drought and flooding events are predicted to occur with greater frequency, requiring mitigation strategies to reduce the associated negative impacts. Retention pond installation schemes designed to capture surface water may be a viable option to reduce water stress during drought periods by supporting irrigation. The retention systems would serve to capture excess spring runoff and extreme rainfall events, reducing flood potential downstream. Additionally, retention ponds may be used for biomass production and nutrient retention. The purpose of this research was to investigate the economic viability of adopting on-farm surface water retention systems as a strategic water management strategy. A retention pond was analysed using a dynamic simulation model to predict its storage capacity, installation and upkeep cost, and economic advantages. The average impact of irrigation application under present day conditions was an increase in crop revenue of $11.38/hectare. However, due to the cost of irrigation and reservoir installation this on average leaves the farmer to pay $148.50/hectare each year. Replacing existing low value crops within the study area with high value potato crops also resulted in a negative net revenue. Irrigated crops under future climate scenarios also experienced a net decrease in revenue due to the associated irrigation and reservoir infrastructure costs. However, gross crop revenue increases were more consistent throughout the future study time periods and required less irrigation water, making irrigation application more beneficial in the future. Farmers who harvest cattails from retention systems for biomass and available carbon offset credits can gain $642.70/hectare of harvestable cattail/year. Cattail harvest also removes phosphorus and nitrogen, providing a monetized impact of $7,014/hectare of harvestable cattail/year. The removal of phosphorus, nitrogen, carbon, and avoided flooding damages of the retention basin itself provide an additional $17,850 to $18,470/hectare of retention system/year depending on the valuations of avoided flooding damages. The recommended use of retention systems is for avoiding flood damages, nutrient retention, and biomass production. This is due to the economic gains these three functions of retention systems provide. The revenue gained from these functions can support farmers wanting to invest in irrigation while providing economic and environmental benefits to the region.

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LIST OF ABBREVIATIONS

AAFC	Agriculture and Agri-Food Canada
API	Antecedent Precipitation Index
CCMEO	Canada Centre for Mapping and Earth Observation
CDEM	Canadian Digital Elevation Model
DRI	Drought Research Initiative
GCM	General circulation models
GEM	Global Environmental Multiscale
GRU	Grouped response unit
IISD	International Institute for Sustainable Development
IPCC	Intergovernmental Panel on Climate Change
LSRCD	La Salle Redboine Conservation District
MASC	Manitoba Agricultural Services Corporation
MCM	Million-cubic-meters
MESH	Modélisation Environmentale Communautaire - Surface and Hydrology
MSE	Mean squared error
NSE	Nash-Sutcliffe efficiency
PCIC	Pacific Climate Impacts Consortium
RCM	Regional climate model
RCP	Representative concentration pathways
SCS	Soil Conservation Service Curve
WP	Winter precipitation

CHAPTER 1

INTRODUCTION

Climate change and its effects have been investigated at various levels from local to global. While it remains difficult to establish a clear understanding of the future effects of climate change, several studies have predicted a general trend of increasing temperature and precipitation over southwestern Canada (Bonsal et al., 2011; Nyirfa and Harron, 2001; Sauchyn et al., 2002; Venema et al., 2010). Canada has experienced an annual average surface air temperature increase of 1.5°C from 1950-2010. Stronger warming trends have been found for the north and west of Canada, with the greatest warming occurring in winter and spring (Vincent et al., 2012; Warren and Lemmon, 2014). These climatic changes are expected to increase potential evapotranspiration and lead to moisture deficits (Venema et al., 2010). Changes in precipitation timing are also expected, resulting in less snow-cover, shorter snow-cover duration, increased winter river flows, and decreased summer flood events (Bonsal et al., 2011; IPCC, 2007a; Venema et al., 2010). Climate change is expected to result in greater variability in cumulative above and below ground water reserves within the Red River Basin, Manitoba. Extreme drought and flooding events are predicted to occur with greater frequency, requiring mitigation strategies to reduce the negative impacts of these events (Bonsal et al., 2011; Pittman et al., 2011; Samarawickrema and Kulshreshtha, 2008; Wheaton et al., 2008). On the Canadian Prairies where 80 percent of Canada's farmland is situated, strategic water management solutions are needed to deal with the uncertainty associated with climate change and its impact on agricultural production (Bonsal et al., 2011; Hearne, 2007; National Research Center, 2013; Wheaton et al., 2008).

Historically, the trend within Manitoba has been to drain agricultural lands of water as quickly as possible in spring using a series of ditches and drains to increase agricultural production (Bower, 2007; Venema et al., 2010).This may leave agricultural lands vulnerable to soil moisture deficits under future climate uncertainty as evapotranspiration quickly removes summer precipitation from the soil (Venema et al., 2010). The creation of on-farm water retention systems, designed to capture and store surface water, may be a viable option that would reduce water stress during agricultural droughts by providing water for irrigation (Pavelic et al., 2012).

The additional benefits provided by retention ponds such as flood mitigation, nutrient retention, and biomass production bolster the benefits of retention systems when they are not required for irrigation (Government of Manitoba, 2014; Grosshans et al., 2012). In Manitoba, cattails are being promoted for bio production and nutrient management as the plant grows most successfully on marginal crop land and in wet areas (Grosshans et al., 2014). Research by the International Institute for Sustainable Development (IISD) has found that cattails at Pelly's Lake, Manitoba not only absorb up to 20 kg/hectare of phosphorus annually, but the plant also removes 160 kg of captured nitrogen/hectare while providing 15-20 tonnes/hectare of biomass. The resulting biomass can be used for various bio products such as solid fuel with a heat capacity of 17 to 20 megajoules/kg (Grosshans et al., 2014). Bio product harvesting also addresses a finding from the Millennium Ecosystem Assessment (Venema et al., 2010). The assessment identifies over-enrichment from nutrients as a critical concern to the environment globally. The removal of phosphorus from this watershed is essential to reducing nutrient loading to Lake Winnipeg, Manitoba. The province of Manitoba has committed to reducing nutrient loading to pre-1970 levels in Lake Manitoba as well as maintaining and improving water quality throughout the province going forward (Bourne et al., 2002; Government of Manitoba, 2014; Grosshans et al., 2014). According to the Lake Winnipeg Stewardship Board (2006), retention basins should be further reviewed to determine how effective and appropriate they can be as a nutrient abatement option in Manitoba.

1.1 Purpose and Objectives of the Study

The purpose of this research is to investigate the economic impact of the adoption of on-farm surface water retention systems as a water management strategy, based on the output of a dynamic simulation model developed for the study area. The first objective of this study is to evaluate the capacity of retention ponds used for irrigation purposes to provide a net economic advantage for farmers not currently utilizing an on-farm water retention system for irrigation application. The second objective is to monetize the benefits of using retention basins for avoided flood damages, nutrient retention, and biomass production. The last objective is to explore the economic advantages associated with retention ponds under future climatic conditions.

1.2 Literature Review

This review begins by outlining the current state of water management in the Red River Valley, Manitoba. The hydrology of this area follows, with a focus on what impacts climate change are expected to have on drought and flood severity and frequency in the Red River Valley. This leads into a discussion on current adaptation strategies being utilized to protect against the effects of water surpluses and deficits on crop yields. Surface water retention systems are put forth as a potentially viable option for dealing with climate uncertainty and these systems multiple benefits are outlined. The review concludes with a discussion of the economics involved in developing water management strategies, specifically the economic benefits surface water retention systems can provide.

1.2.1 Water Management in the Red River Valley, Manitoba

In Manitoba, agriculture is considered to be one of the most vulnerable industries to the negative impacts of climate change (Government of Manitoba, 2014a; Pittman et al., 2011). With the growing awareness of climate change and the effect it will have on agricultural practices there is a need to explore more sustainable approaches to water management on the Prairies (Bower, 2010). The flow and storage of water within the province is critical to maintaining the environment, economy, and livelihoods of its population (Belcher, 1999; Hearne, 2007; Pomeroy, de Boer, & Martz, 2005). Within Manitoba, the issues arising due to climate change are compounded by the provinces already highly variable and unpredictable access to water resources (Pomeroy et al., 2005; Venema et al., 2010). The province is adopting a proactive approach to water management, focusing on protecting water quality while aiming to improve it, and developing strategies for adaptation under uncertain climate projections (Government of Manitoba, 2014a).

Historically, Manitoba’s water management policy focused on altering the landscape to optimize drainage of excess water and subsequently increase its agricultural production. This strategy works well when there is adequate access to water and land use practices do not create nutrient pollution issues (Venema et al., 2010). However, recent years have seen a dramatic increase in nutrient pollution and subsequent diminishing water quality. Additionally, there continue to be suggestions of future drought conditions from general circulation models (Venema et al., 2010).

1.2.2 Hydrology of the Red River Valley, Manitoba

The Red River Valley in Manitoba is predominantly prairie grassland, mostly flat with some rolling hills (Government of Manitoba, 2014b; Hearne, 2007; World Atlas, 2014). Water supplies in the area are stored as snow and ice throughout the fall and winter, and melt rapidly during the spring, providing the majority of water reserves for late spring and summer (Fang et al., 2007). Rainfall also contributes to water supply during late spring and summer, with three quarters of the area's precipitation falling as rain. However, due to the rapid evapotranspiration processes within the Red River Valley, its contribution to water stores and stream flow is low at approximately eight percent (La Salle Reboine Conservation District Staff, 2007; Pomeroy et al., 2005).

Evapotranspiration is driven by evaporation from water bodies and interception from plant canopies and soil surface. Transpiration also occurs from bare soils and plant stomata (Pomeroy et al., 2005). These evapotranspiration processes can often consume all summer precipitation within the Red River Valley (Fang et al., 2007). Any water not consumed by evapotranspiration infiltrates the soil where the high water-holding capacity of prairie soils tends to hold it. However, even this supply of near-surface water can be quickly exhausted by the high net radiation and convection processes of the prairie region (Pomeroy et al., 2005).

1.2.3 Drought

Agricultural droughts are of constant concern in the Prairies (Bonsal et al., 2011; Hearne, 2007; Wheaton et al., 2008). Reductions in precipitation lead to soil moisture deficits and subsequently reduce crop yields, and in extreme cases, cause total crop failure (Samarawickrema and Kulshreshtha, 2008). When an agricultural drought is experienced, not only is soil moisture depleted but groundwater supplies are greatly diminished (Bonsal et al., 2011). Currently, much of the Prairies relies on groundwater (Bonsal et al., 2011). However, these water supplies are unreliable and have stimulated an exploration for alternative water supplies (Pomeroy et al., 2005).

Droughts can also be caused by reductions in annual snowmelt runoff or heat waves which can lead to depleted soil moisture, a reduction in groundwater availability, reservoir level reduction, and diminished stream flows (Bonsal et al., 2011). Evapotranspiration plays a vital role in the development and continuation of drought conditions as the process often dominates the water balance (Armstrong et al., 2010; Pomeroy et al., 2010). Subsequently, soil moisture accumulated in late winter or early spring, when net radiation and convective processes are low and reduce evapotranspiration, is often not enough to offset low snow melt runoff levels or drought conditions during the summer (Bonsal et al., 2011). Surprisingly, the current understanding of droughts in Canada is limited due to fragmented research efforts (Bonsal et al., 2011; Klein et al., 2012). Most studies are conducted in response to droughts, such as the Drought Research Initiative (DRI) initiated after the Prairie drought from 1999-2005 (Bonsal et al., 2011; Bower, 2010; Pomeroy et al., 2010).

1.2.4 Drought and Climate Change

The Intergovernmental Panel on Climate Change (IPCC) has stated that any areas already prone to droughts will undoubtedly be at more risk for drought under future climate change scenarios (Bonsal et al., 2011; Venema et al., 2010). The IPCC's claim is based on the consistent future projections of general circulation models (GCMs) which all point to increased drying and drought risk on continental interiors (Bonsal et al., 2011; Wheaton et al., 2008). Under these future climate scenarios, an increase in both precipitation and temperature is expected (Bonsal et al., 2011). The subsequent evaporative demand created by temperature increases may offset the expected increases in precipitation (Venema et al., 2010). However, the increase in temperature has the potential to negatively impact snow fall events over the winter and reduce the snowfall runoff needed to restore groundwater reservoirs in the spring (Bonsal et al., 2011; Fang et al., 2007; Pomeroy et al., 2005). Additionally, spring thaws may occur earlier than normal as temperatures increase, affecting when soils are receiving moisture and impacting crop growth (Pomeroy et al., 2005). Climate change is predicted to augment the current variable weather trends to increase the duration, severity, and frequency of droughts within the Prairie region (Bonsal et al., 2011; National Research Center, 2013; Venema et al., 2010).

1.2.5 Flooding

Droughts are not the only natural disaster negatively impacting the Prairies. Flooding also has dramatic and wide-spread consequences on agriculture and communities (Bonsal et al., 2011; Bower, 2010). Seasonal floods have been of concern to water managers in Manitoba since the beginning of the nineteenth century (Bower, 2010). Due to the flat topography and subsequent poor drainage of the Prairies, flood waters are often able to spread over large areas (Hearne, 2007). If available water storage is at capacity from previous precipitation events and quick runoff occurs in the spring over frozen ground, runoff can quickly overcome the landscape causing substantial damage (Bower, 2010; Hearne, 2007). Damage to infrastructure such as roads, blown out culverts, or damaged bridges can have a significant economic impact on local municipalities (Agriculture and Agri-Food Canada (AAFC), 2012; Tiessen et al., 2011). Variables such as the timing of the flood, its duration, and water depth will have an impact on a farmer's ability to delay planting or replant (Förster et al., 2008). Implementation of effective water management strategies, while requiring initial investment, reduce costs incurred by farmers and municipalities during flood years (AAFC, 2012; Tiessen et al., 2011).

1.2.6 Flooding and Climate Change

Precipitation and temperature distribution patterns greatly impact flood timing, intensity, and frequency within Manitoba's current climate. Under future climate predictions of increased precipitation events, there is a risk for increases in annual runoff and spring runoff intensity (Mailhot et al., 2010; Simonovic and Li, 2004). Temperature changes will have an impact on snow accumulation and the timing of snowmelt events (Pomeroy et al., 2005; Simonovic and Li, 2004). According to Simonovic and Li (2004), increases to annual temperatures will create earlier flood events as well as earlier flood peaks. It is also expected that future climate change will result in a higher frequency and intensity of multi-day precipitation events that can quickly overcome any strategies in place to deal with sudden excess water (Mailhot et al., 2010).

1.2.7 Adaptation Strategies

In order to prepare for future climate uncertainties, the province of Manitoba and its conservation districts aim to increase their adaptive capacity (Government of Manitoba, 2014a; Manitoba Government, 2014; Pittman et al., 2011). Strategies currently being used on the Prairies include crop insurance, soil and water conservation, improved irrigation (where applicable), exploration of groundwater supplies, as well as the introduction of new infrastructure (Bonsal et al., 2011; Pittman et al., 2011; Wheaton et al., 2008). Infrastructure implementations range from new wells and pipelines to dugouts (Bonsal et al., 2011). Dryland farmers look to increase their drought resiliency by conserving soil moisture and nutrients through crop rotation and minimizing tillage practices (Pittman et al., 2011).

Strategies to deal with flooding in the province are extensive, with channelized drainage systems, such as ditches and culverts, throughout the landscape (La Salle Redboine Conservation District (LSRCD), 2007; Venema et al., 2010). While drainage systems are meant to remove excess water from inundated land quickly, they can actually increase the negative effects of floods by amplifying flood peaks, which then have greater force to cause damage (Venema et al., 2010). Drainage also increases the amount of nutrients being removed from the landscape, subsequently impacting water quality as the nutrients flow into Manitoba's water bodies (Venema et al., 2010).

1.2.7.1 Surface water retention systems

The last two decades has seen increased interest in small water storage facilities globally (Baker et al., 2012; Downing et al., 2006; Li et al., 2000; Oweis et al., 2004; Wisser et al., 2010). Ponds located on agricultural land are being constructed to provide irrigation water, act as sedimentation ponds, for recreational purposes, and water quality control (Chrétien et al., 2016; Downing et al., 2006). Areas of high annual precipitation such as Tennessee, Mississippi, and Great Britain can have up to 4% of their agricultural land allocated to farm ponds. In 2006, researchers suggested that dry regions of India had experienced a 60% increase in the annual growth rate of small reservoirs (Downing et al., 2006; Wisser et al., 2010). It is estimated that globally, farm ponds cover approximately 77,000 km^2 (Downing et al., 2006). Downing et al. (2006) provide an overview of the distribution of farm ponds globally based on annual average precipitation (Figure 1-1).

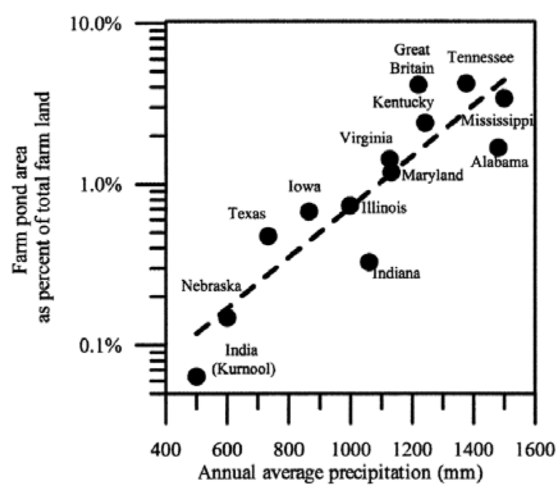

Figure 1-1. Relationship of farm pond surface area to annual average precipitation globally (Source: Downing et al., 2006)

On-farm water retention systems allow for the retention of water captured during spring runoff as well as during precipitation events, either directly or due to transport by surface runoff. This provides water storage that can be drawn on when groundwater supplies become depleted (Pavelic et al., 2012; Vorogushyn et al., 2012). These systems also serve to reduce downstream peak flow and aid in retaining flood waters which reduces associated flood risks downstream (AAFC, 2012; Pavelic et al., 2012). If water is released from the reservoir, they serve to replenish groundwater stores downstream (Pavelic et al., 2012). Under drought conditions these systems enable farmers to draw water from the reservoirs to support crop irrigation (Pavelic et al., 2012). Researchers have found these systems to be effective for increasing and stabilizing crop yields via irrigation in locations such as Texas, Kansas, Kentucky, India, and Thailand (Arnold and Stockle, 1991).

Water retention systems can be classified into three main types on the Prairie landscape. The first is a dry flood-control dam characterized by a lack of water storage capacity. These dams act to slowly release water by forcing flow through a small pipe at the foot of the dam reducing flood peaks downstream (AAFC 2012; Tiessen et al., 2011; Wall et al., 2011). To reduce their impact on the landscape, they are often integrated into existing roadways (Tiessen et al., 2011). Back-flood dams are another popular form of water retention systems that enable temporary storage of shallow waters (about one meter) over a large expanse of agricultural land for a minimum of two weeks. Water is eventually released via a manual gate each season providing groundwater recharge (AAFC 2012; Tiessen et al., 2011; Wall et al., 2011). Multi-purpose dams are similar in design to dry flood-control dams and are additionally designed to store 15-20% of their full capacity during the summer months for the purposes of irrigation or cattle watering. They are drained each year to ensure the reservoirs full capacity is available each spring for runoff (AAFC 2012; Tiessen et al., 2011; Wall et al., 2011).

Currently, each retention system requires a unique engineered plan which situates the dam or pond in a strategic location considering land drainage and hydrological connectivity along with the water retention time required (Ali et al., 2013; Baker et al., 2012; Chrétien et al., 2016; Paul, 2003; Tiessen et al., 2011; Woltemade, 2000). On-farm water retention structures can vary considerably in size. For example, sixty documented water retention structures in Manitoba, Canada range in size from 6000 m^2 to 11 km^2 with an average size of 384,000 m^2. Water storage of the same structures range in capacity from 365 m^3 to 12,000,000 m^3 with an average storage capacity of 365,000 m^3 (Manitoba Conservation District Association, 2014). The proper placement and design of retention systems can allow for additional environmental benefits like restoring or protecting wetlands (Government of Manitoba, 2014a). While retention system placement may occasionally provide solely a water retention benefit, whenever possible retention areas should be placed in natural wetland depressions to ensure restoration or maintenance of nearby wetlands affected by the retention system project. A loss of capacity over time also needs to be considered as sediment deposits build up. The rate of build up will vary based on the size of the reservoir, amount of inflow and sediment content, local geology, rainfall distribution, vegetation, soil type, the ability of the reservoir to retain sediment and the type of reservoir operation (Jothiprakash and Garg, 2008; Tiessen et al., 2011; Wisser et al., 2010).

Surface water retention systems have shown success in reducing nutrient and sediment loading in various locations worldwide. Tiessen et al. (2011) provides several examples from the literature on retention systems in America and Europe shown to effectively reduce nutrient loading. A runoff detention pond in Oklahoma, USA reduced sediment discharge downstream by 82%, total nitrogen by 56%, and total phosphorus by 60% (Sharpley et al., 1996). Kovacic et al. (2006) reported a reduction in total nitrogen of 38% and 56% in total phosphorus loading from a constructed wetland (a detention basin formed by berms adjacent to a stream) in Illinois, USA. A shallow predam, a small reservoir aimed at improving water quality of a larger main reservoir downstream, in Luxembourg was found to retain total phosphorus up to 60% and a deep predam retained up to 82% (Salvia-Castellvi et al., 2001; Tiessen et al., 2011). A small dam in Spain reduced total phosphorus loads downstream by over 25% (Avilés and Niell, 2007). Small ponds in Finland and Sweden reduced total phosphorus loading by 17% and constructed wetlands in Norway and Finland reduced total phosphorus loading by 41% (Tiessen et al., 2011; Uusi-Kämppä et al., 2000).

In Manitoba, small on-farm surface water retention systems are scattered throughout agricultural watersheds. The South Tobacco Creek Watershed is home to twenty-six dams providing management of almost 30% of the watersheds drainage area (AAFC 2012). The watershed is now home to five dry dams, six back-flood dams, and fifteen multi-purpose dams. Each dam was designed to retain 20-25 mm of runoff at full capacity from their catchment area (Tiessen et al., 2011). These dams' capacity to reduce flood risk have been under study since the 1990s. The Watershed Evaluation of Beneficial Management Practices (WEBs) program, an Agriculture and Agri-Food Canada (AAFC) research program began in 2004 to expand the research on the South Tobacco Creek Watershed dams to include sediment, nitrogen, and phosphorus loadings downstream (AAFC 2012). The WEBs program chose to focus on two dams in the study area, a dry flood control dam with a 45,000 m^3 capacity reservoir located in the north western section of the watershed and a multi-purpose dam with a 60,000 m^3 capacity in the south-west of the watershed. The differences between these systems had little effect on their ability to reduce sediment, nitrogen and phosphorus export downstream. Both the dry flood control dam and the multi-purpose dam were effective in reducing total suspended sediment (65-85% reduction), particulate nitrogen (41-43% reduction during snowmelt, 7-11% reduction from summer rainfall events), and particulate phosphorus (27-38% reduction in snowmelt runoff) (AAFC 2012). The entire dam system of the watershed provided a reduction in peak flow of 9-19% from spring snowmelt runoff and 13-25% from rainfall runoff (AAFC 2012). Another on-farm retention pond in Saint-Samuel, Quebec was found to reduce peak flows by 38%, on average, from rainfall runoff events (Chrétien et al., 2016). The pond was also effective at removing total suspended sediment, total nitrogen, and total phosphorus with mean removal efficiency ratios of 50-56%, 42-52%, and 48-59% respectively.

1.2.7.2 Irrigation

One of the most successful strategies for dealing with uncertain water availability is irrigation. With irrigation, reductions to crop yields do not occur under drought conditions. Often, farmers may actually see an increase in crop yields. This is due to high temperatures increasing evaporation in combination with the unlimited water supply (Pittman et al., 2011). Increases to evapotranspiration enhance growth, especially when there are no constraints on moisture or nutrients (Samarawickrema and Kulshreshtha, 2008). According to Pittman et al. (2011) in the rural municipality of Rudy, Saskatchewan, irrigation farmers during the Canadian drought of 2001-2002 had financial gains of over a million dollars while dryland, or non-irrigating, farmers lost $5.5 million in 2001 and $4.5 million in 2002.

1.2.7.3 Bio products

Another benefit of water retention systems is their capacity to support the growth of bio products. Bio products are beneficial for the production of bioenergy, nutrient retention and extraction, and carbon offsets (Government of Manitoba, 2014b; Grosshans et al., 2014). Plants when alive or recently harvested create biomass, or biological material with stored energy from sunlight (Natural Resources Canada, 2016a). Biomass is growing in importance globally for its use as an energy source, its capacity to be converted into biofuel, and its value in reducing global dependence on fossil fuels (Grosshans et al., 2012a, 2014; Natural Resources Canada, 2016a). Biomass has the capacity to absorb carbon dioxide from the atmosphere, making biofuel a low carbon renewable resource (Grosshans et al., 2012a). Canada has access to a variety of biomass resources through agriculture, forestry, and municipal waste (Natural Resources Canada, 2016b; Tampier et al., 2003). Bioenergy from these resources has become an important renewable energy source in the country. Seventy power plants devoted to bioenergy are scattered across Canada providing 6% of the country's total energy (Natural Resources Canada, 2016c). As of 2013, Canada was the fifth highest producer of liquid biofuels generating 2% of global biofuel production. The United States, Brazil, the European Union, and China hold the top four spots for biofuel production globally (Natural Resources Canada, 2016b).

The province of Manitoba is working towards increasing their production of renewable resources to aid in reducing the energy sectors greenhouse gas emissions (Government of Manitoba, 2011). Biomass harvesting for the purpose of replacing coal also aids in Manitoba's ban on using coal for space heating (Grosshans et al., 2014). In 2006, the Lake Winnipeg Stewardship Board suggested reviewing areas of unharvested vegetation for biofuel potential. The Board also pointed to a review of benefits associated with harvesting wetland plants in order to remove their stored nutrients from the environment. This would prevent dead and decaying plant matter from releasing dissolved nutrients back into the aquatic environment (International Institute for Sustainable Development (IISD), 2011; Lake Winnipeg Stewardship Board, 2006).

Cattails (*Typha latifolia)* are one biomass resource being promoted for their bio production capacity and nutrient management. This naturally occurring plant is found in wetlands throughout Canada and the United States. Cattails grow most successfully on marginal crop land and in wet areas and thus do not take away from prime agricultural lands and food production (Grosshans et al., 2014; Maddison et al., 2005; Pratt et al., 1984). Harvesting cattails can subsequently provide landowners with additional revenue on underutilized land (Grosshans et al., 2014; Lake Winnipeg Stewardship Board, 2006; Pratt et al., 1984). By harvesting wetland plants such as cattails, surface water retention sites gain the additional benefit of providing biomass and increased nutrient management (Government of Manitoba, 2014a; Grosshans et al., 2014). Manitoba's Surface Water Management Strategy (2014a) states that water storage and associated release strategies should optimize production and harvest of biomass resources to remove phosphorus from the aquatic environment. Removing these nutrients from the landscape via harvest reduces downstream nutrient loading. This is essential for combating algal blooms and increasing water quality in aquatic environments such as Lake Winnipeg, Manitoba (Grosshans et al., 2014).

Retention systems that hold water in the reservoir throughout the growing season increase the growth potential of cattails. The excess moisture drowns out grasses that compete with cattails while providing improved soil moisture conditions for cattail germination (Grosshans et al., 2014). When compared to other sources of biomass, cattails also have the highest average yield with the lowest time to maturity (Dubbe et al., 1988; Laffont-Schwob et al., 2015; Pratt et al., 1984). Cattails have good densification properties, high quality fibre and high energy density making them suitable for biofuel development (Grosshans et al., 2014). The plant not only absorbs up to 20 kg/hectare of phosphorus as it grows, but it also removes 160 kg of captured nitrogen/hectare while providing 15-20 tonnes/hectare of biomass. Table 1-1 provides an overview of eight biomass yields and times to maturation (Grosshans et al., 2012a).

Table 1-2 outlines the percentage content of carbon, hydrogen, and nitrogen in seven typical biomass resources.

Table 1-1. Average yield and time to maturity for eight biomass materials. Adapted from Grosshans et al. (2012a).

Biomass	Average Yield (T/Ha)	Time to Maturity
Cattail (*typha* species)	14.7 – 18.8 [a], 12 – 42[b]	90 days
Panicum virgatum (switchgrass)	9.1 – 13.5	3 years
Miscanthus (silvergrass)	6.3 – 48.3	3 – 5 years
Trees (willow (*salix* species), poplar (*Populus*))	7 – 10	3 years, 6 – 12 years
Triticum aestivum (wheat) straw	1.8 – 2.4	90 – 100 days
Maize stover	5.1	110 – 120 days
Linum usitatissimum (Flax) residue	1.2	99 – 110 days
[a]Grosshans et al., 2011 [b] Dubbe et al., 1988		

Table 1-2. Cattail carbon, hydrogen, and nitrogen content compared to seven typical biomass resources. Adapted from Grosshans et al. (2012a).

Biomass	Carbon (%)	Hydrogen (%)	Nitrogen (%)
Cattail	38.8 to 43.6	5.39 to 5.74	0.83 to 1.28
Wood (various)	47.6 to 52.6	6	0 to 0.35
Straw	42	5.1	0.38
Maize stover	43.7	-	0.61
Coal (Anthracite)	80		0.90
Coal (Bituminous)	52.5 to 81.7		1 to 1.5
Coal (Lignite)	40.1		.70
Natural Gas	75	24	.9

Biomass burners and pellet stoves can burn pellets created from the harvested cattails. Cattail biomass converted to a solid fuel has a heat capacity of 17 to 20 megajoules/kg (Grosshans et al., 2014). Table 1-3 provides an energy value comparison between cattails and common biomass and fuel sources. Once cattail pellets are burned, the resultant ash can then be utilized for fertilizer due to its high levels of phosphorus (Grosshans et al., 2012b; IISD, 2011). IISD has shown at a study site in Manitoba with an area of 253 hectares, cattail harvest can remove up to 5000 kg of phosphorus from the system each year (Grosshans et al., 2014; LSRCD, 2013). Wetland habitats also benefit from cattail harvesting as their removal allows for more sunlight to stimulate new plant growth (IISD, 2011).

Table 1-3. Energy value comparison between cattails and common biomass and fuel sources. Adapted from Grosshans et al. (2012a).

Biomass	Calorific Value MJ/Kg
Cattail Cattail pellet (no binder) Cattail pellet (starch binder)	17.29 – 18.2 19.89 16.80
Wood pellet (standard) Wood (15% mc) Wood chips	16.9 – 18.0 15.0 – 22.3 10.4
Wheat straw (dry) Wheat straw (20% mc)	17.86 13.74
Flax straw (dry) Flax straw (20% mc)	19.97 15.43
Maize stover	17.6
Helianthus annuus (sunflower) hulls	19.7
Propane	46.37
Natural gas	48
Fuel oil	37
Coal (anthracite) Coal (bituminous) Coal (lignite)	29.5 20.9 – 33.4 15.31

Water retention systems are ideal sites for nutrient removal as they act as concentration sites within a watershed for collecting excess nutrients allowing for maximum nutrient removal from bio products such as cattails. The removal of phosphorus from watersheds is essential to reducing nutrient loading to Lake Winnipeg, Manitoba. The province of Manitoba has committed to reducing nutrient loading to pre-1970 levels in Lake Manitoba as well as maintaining and improving water quality throughout the province going forward (Bourne, Armstrong, & Jones, 2002; Government of Manitoba, 2014b; Grosshans et al., 2014). Bio product harvesting also addresses the finding from the Millennium Ecosystem Assessment which identifies over-enrichment from nutrients as a critical concern to the environment globally (Venema et al., 2010).

1.2.8 Economics

Developing water management strategies in the face of uncertain climate change is further substantiated using economic criteria. Droughts on the Prairies are considered the most costly natural disasters that face Canada, impacting agricultural production as well as jobs (Bonsal and Prowse, 2006). With the Prairies providing the majority of Canada's agricultural cropland, a Prairie drought has the ability to greatly reduce exports and livelihoods of affected provinces. The drought of 2001-2002 resulted in a loss of 41,000 jobs and 3.6 billion dollars due to decreases in crop yields (National Research Center, 2013). Farms without irrigation face limited returns on their crops under moisture deficit, while those using irrigation require access to water reserves (Pittman et al., 2011). When moisture is not present during the crop growing season, returns for dry land agricultural operations are severely limited (Pittman et al., 2011).

Changes in temperature and precipitation expected with climate change will impact a wide range of variables affecting the productivity and returns of annual crops. Alterations in the growing season length, frost timing, heat waves, precipitation, and moisture availability will be witnessed with temperature and precipitation increases. This will require farmers to be ready to adapt to new climatic patterns (Wall and Smit, 2005). The uncertainty associated with climate also increases risk for farmers, requiring water management solutions that will provide benefits to farmers under all conditions and reduce risk (Pittman et al., 2011; Wall and Smit, 2005). Economic consequences of drought or flooding events will depend on the agricultural and water management sectors success in preparing and adapting for climatic extremes (Bonsal et al., 2011).

Adaptation does not come without barriers. Access to funds for irrigation infrastructure can be difficult to attain. A large irrigation installation can cost millions of dollars that is simply not feasible for some communities (Bonsal et al., 2011). It becomes important to consider the economic costs and benefits associated with different adaptation strategies as management decisions are often based on this information (Belcher, 1999). While irrigation provides an economic gain during drought years it also increases operational costs for water supplies (Samarawickrema and Kulshreshtha, 2008). The size and holding capacity of retention systems also need to be considered to maximize benefits while limiting the initial costs of building a surface water retention system (Gohar et al., 2013). Placement of retention ponds can have a big impact on their affordability as earthwork involved can contribute up to eighty percent of the total cost of installation and upkeep (Gohar et al., 2013). The size of the farm and amount of crop requiring irrigation will influence the size of retention pond best suited for the area. According to Gohar et al. (2013), farmers with a medium sized reservoir with a holding capacity of 2310 million-cubic-meters (MCM) can increase their yearly income by sixteen percent in comparison to small scale reservoirs with a holding capacity of 770 MCM. Eight crops were used in the analysis: wheat, alfalfa, rice, cotton, melon, potato, tomato, and legumes. However, under future climate scenarios seeing a reduction in water supply of twenty percent over twenty years, the smaller investment required for a small reservoir provided a more stable income then going with a larger reservoir design (Gohar et al., 2013). Future climate change may result in agricultural systems becoming increasingly risky, requiring the adoption of risk management tools such as water retention systems.

1.2.9 Summary

If the timing of seasonal precipitation begins to change and temperatures continue to rise under climate change there will be severe effects on agriculture, ecosystems, water runoff rates and quantities as well as groundwater stores. In order to increase the adaptive capacity of the communities within the Red River Basin, Manitoba in the face of uncertain climate change, best management strategies such as multi-purpose retention systems need to be implemented. Strategies need to provide drought proofing of crops as well as limiting damages caused by floods in non-drought years. Strategies should also allow for sustainable water management by providing multiple benefits when possible such as bio production and nutrient retention (Government of Manitoba, 2014a).

1.3 Thesis Structure

This thesis is composed of four chapters: an introductory chapter, a methods chapter, a results chapter, and a conclusions chapter. Chapter 1 begins with an introduction, which places the research contextually, followed by the purpose and objectives of the study. A literature review is provided outlining the current and predicted future state of water management in the Red River Valley, Manitoba. The literature review then provides a review of adaptation strategies available to promote more sustainable water management under future climate uncertainty. The chapter concludes with a discussion of the economic feasibility of the outlined adaptation strategies.

Chapter 2 details the methods used for this research and is divided into three sections. An overview of the chosen modeling approach begins the chapter. A detailed explanation of the modeling system developed for this research follows. The next section of Chapter 2 introduces and details the model setup for the two hydrologic models used in providing initial reservoir volume and daily streamflow inputs to the modeling system. The last section explains the selection of climate data and its application for this research.

Chapter 3 provides the results of this research. The chapter begins with a comparison of the two hydrologic models used in the study and the modeling system sensitivity analyses results. Next, the results are presented, divided by objective. The thesis discussion and conclusions are found in Chapter 4 with a section on potential policy recommendations. The discussion leads into a section outlining the limitations of this study, potential for future work, and the contribution this research has to sustainability. The chapter concludes with a discussion on how this research is scholarly and societally relevant.

CHAPTER 2

METHODS

This chapter is divided into three sections. It begins with a description of the study site chosen for this research. This is followed with a discussion on the selected modeling approach selected for this study and details the modeling system developed for this research. A description of the sensitivity analyses performed and a formal model evaluation will conclude the section. The next section will detail the two differing hydrologic models used in generating initial reservoir volume and daily streamflow values. A comparison of outputs from the two hydrologic models will be provided in Chapter 3. Concluding this chapter will be a section on climate change. Climate change data, data selection for this study and its application in meeting objective three of this research will be addressed.

2.1 Study Site

Pelly's Lake site in south central Manitoba was chosen due to its pre-existing surface water retention system offering multiple benefits. The system also has the capacity to be developed for irrigation due to the reservoir's large water storage capacity and location. Landowners in the area in combination with the La Salle Redboine Conservation District (LSRCD) agreed to create a back flood system offering multiple benefits. The current land use at Pelly's Lake was not meeting landowners goals (LSRCD, 2013). Previous attempts to drain the land using ditches and drains where Pelly's Lake is located in order to optimize hay production had failed. Landowners were left with a wetland area filled with cattails due to the area being fed by an underground spring (LSRCD, 2013). The LSRCD is a non-profit organization formed in 2002 covering an area of approximately 5200 km^2 in southern Manitoba. Their mandate is to protect the natural resources of their district while promoting sustainable development (LSRCD, 2015a).

Pelly's Lake has now been engineered with a dike installation to allow for floodwater retention, groundwater recharge, increased hay production, and nutrient removal in crop biomass (Grosshans et al., 2012). The reservoir, which has a storage capacity of 2,100,000 m^3, allows for rain runoff and spring freshet to be captured each year (Armstrong et al., 2010; Pomeroy et al., 2011). The surface area of the lake is 1,210,000 m^2, with the dike installation located at the north east end (Figure 2-1). Other potential study sites were smaller, single use, and not as representative installations. Pelly's Lake offered an opportunity to determine the economic benefits of large, multifunctional retention systems on the Manitoba landscape. The site offered collaborations with the conservation district and researchers at the IISD performing research at the site. Additionally, the location had the most available data for the study over other potential study sites.

Pelly's Lake is situated within the Red River Basin, a predominantly flat land area with prime agricultural lands (Hearne, 2007). The Pelly's Lake watershed is dominated by highly productive cropland consisting of well drained, loam to clay loam, mixed till soils in the rolling upland portion of the watershed (Stephenfield Lake Watershed Round Table, 2005). The area has a semi-humid climate with average annual precipitation ranging from 480-560 mm. A variety of annual crops are produced in the watershed, including spring wheat, canola, barley and some forage production such as alfalfa. Imperfectly drained soil conditions dominate the more level lacustrine soils below the rolling upland portion of the watershed (Stephenfield Lake Watershed Round Table, 2005). Drainage as well as water retention potential in this area is poor which causes widespread flooding during times of excess water (Hearne, 2007; LSRCD, 2007). Documentation in the area indicates that the soil types may not be ideal candidates for irrigation. However, this study was more interested in determining the economic feasibility of developing irrigation and if ample water could exist in on-farm retention systems to support irrigation practice (Langman, 1986, 1989).

(a)

(b)

Figure 2-1. Pelly's Lake, Manitoba. (a) Pelly's Lake situated within the watershed boundary. Dike location is illustrated by the rectangle located at the north east end of the lake; (b) Concrete dike installation at Pelly's Lake on the left with a view of the lake to the west of the dike.

2.2 STELLA Modeling System

2.2.1 Introduction

The interactions and complex feedback loops inherent in combining ecological and economic systems required a complex non-linear system dynamics approach which embraces the links between these systems (Belcher, 1999; Costanza et al., 1993; Low et al., 1999). A system dynamics method allowed for hydrologic, reservoir, plant growth, irrigation, and economic modules to be created on a common spatial and temporal scale (Costanza et al., 1998). Software available for developing system dynamic models provides user friendly interfaces which do not require extensive modelling knowledge. The software also provides an interface to communicate visually how the various components of the modeling system are interacting. This offers a better method of communicating the complexity of the modeling system to the end user than conventional code-based models.

A system dynamic model was chosen over existing crop models such as APSIM and DDSAT (APSIM Initiative, 2016; DDSAT Foundation, 2016; Keating et al., 2003) for several reasons. Several system dynamics models have been developed for water resources management (Mirchi et al., 2012; Qaiser et al., 2013). A system dynamics approach has been used successfully by several researchers on the Canadian Prairies (Belcher et al., 2004, 2003; Chen and Wei, 2014; Hassanzadeh et al., 2014; Simonovic and Li, 2004). The researchers involved had previous experience using the system dynamics approach (Belcher et al., 2004). A simplified model was commensurate with the dataset available. System dynamics also provided a method for model development that can be easily expanded for future research to include new modules or expansion of the developed modules from a local to regional scale. Finally, as the current research was focused on the multiple benefits of retention basins, the model needed to contain a strong component for modeling reservoirs.

2.2.2 Modeling Components

The modeling software STELLA, a program designed specifically for modeling complex system dynamics, was adopted as the modeling platform for this study. The STELLA system dynamic modelling software has also been used in a variety of biological and ecological sciences (Belcher et al., 2004; Costanza et al., 2002; Ouyang et al., 2010). The STELLA software allows for the development of a dynamic modeling system using four main tools: (1) Stocks, a variable which accumulates and stores values. (2) Flows, which define inflow and outflow from a stock.

(3) Converters, which hold information such as constants, unit conversions, functions, or time series. (4) Connectors, which act to connect features, variables, and elements to one another indicating the relationship between components. Each stock, flow, and convertor allows for the input of values and equations to specify the relationship amongst the model components (ISEE, 2016).

The modeling system developed for this research is comprised of five modules: 1) hydrologic; 2) reservoir; 3) irrigation; 4) plant growth; 5) economic (Figure 2-2). The first module, hydrologic, allowed for streamflow input into the reservoir and initial reservoir volume from spring freshet to be added to the model. The reservoir module then calculated reservoir output based on pre-existing dike parameters, evapotransiration processes, runoff, and withdrawals taken for irrigation purposes. The irrigation module consisted of irrigation withdrawals and precipitation during the growing season informing water volume available for crops. The plant growth module modeled crop yields using water sufficiency curves and maximum crop yields specific to each crop. The economic module used crop yield outputs in combination with crop prices, crop production costs, and infrastructure costs to determine net revenue for each simulation year.

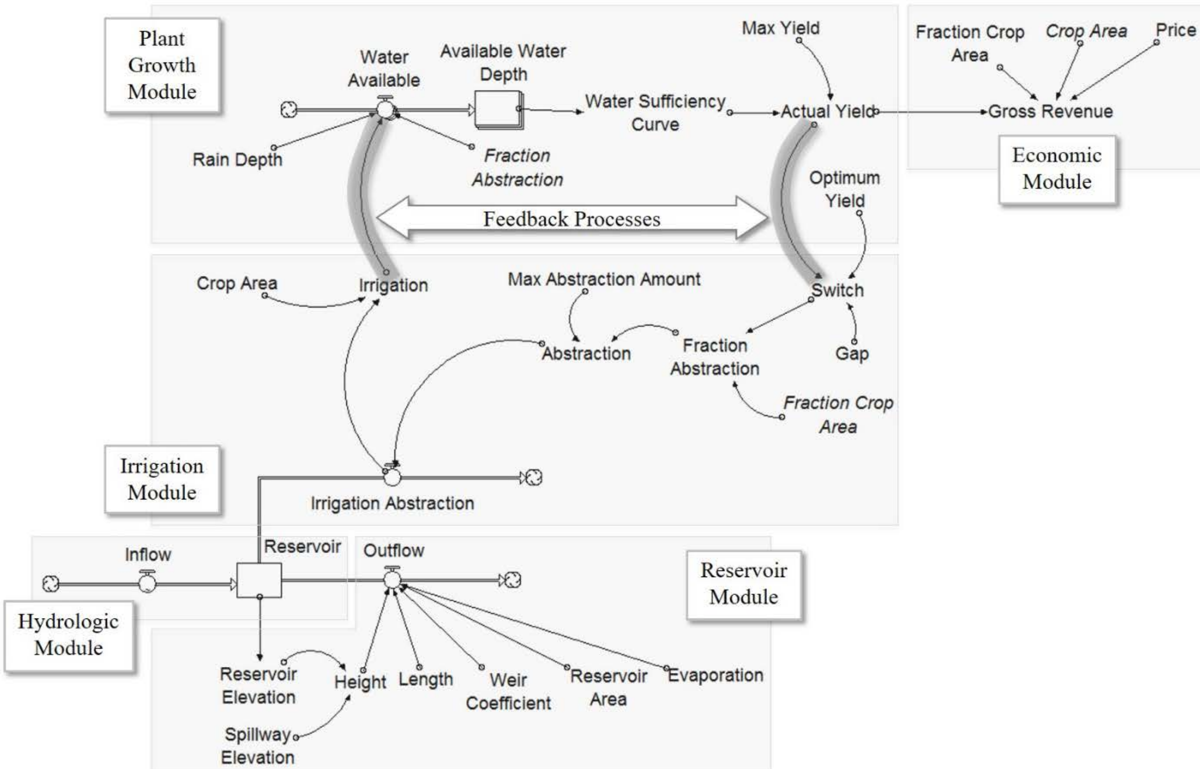

Figure 2-2. Stock-flow diagram of five model system components: (1) MESH inputs, (2) reservoir module, (3) irrigation module, (4) plant growth module, and (5) economic module. Feedback processes are noted and highlighted in grey.

2.2.3 System Scale Considerations

The modeling system was developed based on a daily time step using a growing season simulation period running from April through September each year. The daily time step captured short-term components of the system while allowing for multiple years to be analyzed for a long-term analysis of the problem (Belcher, 1999). The simulation period allowed for yearly spring freshet and precipitation events to be simulated. The time period 2002 to 2014 was modeled based on relevant climate condition data to capture precipitation variation and provide a longer-term evaluation of the potential for retention ponds to provide water for irrigation. Precipitation during the growing seasons of 2002 to 2014 ranged from 126 mm to 491 mm, with an average rainfall of 338 mm (Government of Canada, 2015). The analysis began in 2002 as 2002 and 2003 represented years that had above average crop insurance claims in Manitoba. Province wide, 2002 experienced the third highest insurance claims for drought and dry seedbed between 1994 and 2014 at $19.6 million, while 2003 experienced the second highest claims at $25 million dollars (Manitoba Agricultural Services Corporation (MASC), 2015). The year 2004 was excluded from analysis when using MESH hydrologic input due to incomplete hydrologic modeling data. Spatially, the study was confined to the watershed surrounding the study site as this was the area with the potential to directly benefit from the retention pond establishment.

With respect to cropping systems developed in the model, since potato is the most commonly irrigated crop in Manitoba, but was not present in the study watershed, the model was also run replacing barley crops with potato crops (Gaia Consulting Limited, 2007; Government of Manitoba, 2016). Due to the low moisture deficits experienced in Manitoba, primarily dryland crops such as cereals and oilseed, which are also lower value crops, do not provide enough financial benefit to merit irrigation (Gaia Consulting Limited, 2007). Using a high value crop such a potato for irrigation, how much of the study cropland would need to be converted to potatoes in order to receive a positive net revenue from irrigation. This was considered a reasonable assumption since the irrigation system removed available water as one of the primary constraints to potato production in the study landscape. The year 2006 was chosen for this simulation as it was the driest year within the study time period. The highest recorded, with recording beginning in 1991, application of irrigation to potato also occurred in 2006 (Gaia Consulting Limited, 2007). With potato crops replacing barley, the percentage of crop allocated to potato was set to 5%, 20%, 30%, 50%, and 100%. Simulations were run with no irrigation, irrigation distributed across all four crops, as well as irrigation isolated to only the potato crops. Each module is explained in terms of stocks, flows, converters, and connectors in the following sections with a detailed description of the parameters and equations used in the model. A list of parameters used within the dynamic model are summarized in Table 2-1.

Table 2-1. Parameter values, units, and sources for the modelling system.

Parameters	Value	Units	Source
Daily discharge values (inflow)	Daily flow values for April 15th – September 15th each year	m^3/day	Hydrologic models, Section 2.2
Initial reservoir volume	Cumulative flow values from March to April 15th each year	m^3	Hydrologic models, Section 2.2
Outflow	Equation 2-1	m	Established engineering equation for outflow over a rectangular weir

Weir coefficient	0.6	dimensionless	Established engineering value
Length (L)	12	m	Engineering drawings
Height (H)	Equation 2-1	m	Established engineering equation
Reservoir elevation	Equations 2-3	m	Engineering storage rating curve
Spillway elevation	379.1	m	Engineering drawings
Evaporation	April (0.00182) May (0.00422) June (0.00460) July (0.00454) August (0.00469) September (0.00346)	m/day	1981-2010 mean monthly evaporation values converted to daily values at Brandon, MB (Government of Manitoba, 2015)
Reservoir Area	85,867,480	m^2	ArcGIS
Total crop area	66,976,634	m^2	ArcGIS; (Government of Manitoba, 2014c)
Max irrigation abstraction amount	15,000	m^3	Calibration
Rain depth	Variable	mm/day	Environment and Climate Change Canada (Government of Canada, 2015b)
Max Yield	Alfalfa (0.000672126) Barley (0.000376588) Canola (0.000224124) Spring Wheat (0.000336063) Potato (0.004)	tonnes/m^2	Government of Manitoba, 2015a
Crop Prices	Alfalfa (132.28) Barley (173.23) Canola (418.87) Spring Wheat (238.83) Potato (244.93)	$/tonne	Government of Manitoba, 2015a
Fraction Crop Area	Alfalfa (.11) Barley (.05) Canola (.46) Spring Wheat (.38)	dimensionless	CANSIM

Fraction Crop Area for 2006 Potato Simulation (as crop area allocated to potato increases)	Potato (.05, .20, .30, .50, 1) Alfalfa (.11, .06, .033, 0, 0) Canola (.46, .41, .377, .30, 0) Spring Wheat (.38, .33, .29, .30, 0)	dimensionless	CANSIM

2.2.4 Hydrologic Module

The first flow within the modeling system was *inflow*. Daily discharge values (in m^3/day) were input in graphical format into this flow for the growing season of one year, 154 days (April 15 – September 15). Each time a new year was simulated, new discharge values were input. *Inflow* flowed into the *reservoir* stock. An initial reservoir volume (in m^3) was set based on the cumulative flow values from March – April 15th of each year. Hydrologic input was provided by two different hydrologic models, outlined in Section 2.2. Model results using inputs from each hydrologic model were compared, refer to Chapter 3.

2.2.5 Reservoir Module

Two flows were drawn from the *reservoir* stock, *outflow* and *irrigation abstraction*. The emergency spillway and gates for the dike were included in the model to enable calculation of outflows under flood conditions and release of reservoir water, respectively. Values were obtained from the provided engineering drawings for the dike. *Outflow* was determined by the following equation for outflow over a rectangular weir:

$$Outflow = ((3)(Weir_{Coefficient})(L)(H)^{1.5}(86400)) - ((Evaporation)(Reservoir\ Area)) \qquad (2\text{-}1)$$

where the $weir_{Coefficient}$ was a converter set at 0.6 based on standard engineering convention, length (L) a converter with a value of 12 meters to indicate the length of the weir, *86400* was a converter to adjust the outflow value from m^3/s to m^3/day, and height (H) was determined in a converter by the following formula:

$$\mathrm{H} = if\ (Reservoir_{Elevation} - Spillway_{Elevation}) > 0\ then\ (Reservoir_{Elevation} - Spillway_{Elevation})\ else\ 0 \qquad (2\text{-}2)$$

$Reservoir_{Elevation}$ was another converter holding the following equation derived from the engineering storage rating curve:

$$Reservoir_{Elevation} = \left(9\ x\ 10^{-7}\right)(Reservoir) + 378.23 \qquad (2\text{-}3)$$

with reservoir values coming from the *reservoir* stock in m^3/day. The $Spillway_{Elevation}$ converter in Equation 2-2 was set to 379.1 meters. Returning to Equation 2-1, the *reservoir area* converter was set at 85,867,480 m^2. *Evaporation* values were the 1981-2010 mean monthly evaporation values at Brandon, Manitoba. These values were provided by the Government of Manitoba (2015). The mean monthly values were divided by the number of days in the month to give an average daily evaporation value in meters that was input into the evaporation converter graphically. Evaporation values drawn from these mean values were applied to all years within the study period. This method of determining evaporation was used due to lack of information available to calculate evaporation at the study site.

2.2.6 Irrigation Module

To model the effects of irrigation of crops on reservoir water levels, a variable allowing for water abstraction, *IrrigationAbstraction,* was included in the model. For the purposes of this model, available water was applied to the four most common crops produced in the watershed. The total crop area of the watershed is 6,698 hectares. The four most prevalent crops within the local Victoria and Lorne census areas as of 2011 are canola, spring wheat, alfalfa, and barley (Government of Canada, 2011). As potato is the most commonly irrigated crop in Manitoba, but was not present in the study watershed, the model was also run replacing barley crops with potato crops for the 2006 year to determine the changes to economic benefits. The equation for *IrrigationAbstraction* is:

$$IrrigationAbstraction = abstraction_{canola} + abstraction_{wheat} + abstraction_{barley} + abstraction_{alfalfa} \qquad (2\text{-}4)$$

Where:

$$Abstraction_{crop} = (max\, abstraction\ amount)(fractionAbstraction) \qquad (2\text{-}5)$$

The *max abstraction amount* was set at 15,000 m^3/day. This value was found via calibration to allow the reservoir to drain slowly while still providing sufficient water for irrigation until the end of the growing season. *FractionAbstraction* is explained in Equation 2-6.

Water abstracted from the reservoir for crop irrigation, in combination with rain depth, provided the water available for crops (Belcher et al., 2004). Irrigation was applied (*Switch = 1*) if the available water for a crop (*Crop = Canola, Wheat, Barley, or Alfalfa*) was only sufficient to provide 80% of that crop's optimum yield at a point in time during the growing season. A value of 80% was chosen for *gap* (Equation 2-7) as water stress causing yield reduction happens when water available for plants falls below 60% of optimum (Grinder, 2000). To ensure water available for plants did not reach that level, irrigation began once a threshold for available water enabling 80% yield was met on or after May 15th (day 30, included in Equation 2-7). This ensured water was only applied to a crop when sufficient water for optimal growth was not being met without irrigation. A feedback loop within the model between actual yield and the switch used to initiate the withdrawal of irrigation was thus included. The withdrawn irrigation water created a feedback to water available for crops, impacting actual yield. As water available to plants was increased, actual yield could be optimized to improve net revenue. The algorithm for the fraction of the amount available for irrigating each crop $fractionAbstraction_{Crop}$ became:

$$
\begin{aligned}
&if\ \textstyle\sum_{Crop} Switch_{Crop} > 0 \\
then \quad & denominator = \textstyle\sum_{Crop} Switch_{Crop} * fractionArea_{Crop} \\
& fractionAbstraction_{Crop} = \frac{Switch_{Crop} * fractionArea_{Crop}}{denominator} \\
& else \quad (0)
\end{aligned}
\qquad (2\text{-}6)
$$

This algorithm served to direct the water to each crop as needed and to ensure water was not applied to a crop when sufficient water for optimal growth was being met without irrigation. $FractionArea_{Crop}$ was determined based on the fraction of each crop in the crop area. Canola comprised 0.46 of the crop area, wheat comprised 0.38, barley comprised 0.05, and alfalfa comprised 0.11 of the crop area. These values were based on historical patterns within the study area (Government of Canada, 2015b; Government of Manitoba, 2014c). *Switch* for each crop was determined by the following equation:

$$Switch_{crop} = if\ Actual_{yield} < (gap * Optimum_{Yield})\ and\ time > 30\ then\ 1\ else\ 0 \qquad (2\text{-}7)$$

$Optimum_{yield}$ represented the maximum, or optimal yield of each crop based on optimal water requirements being met and was constant for each crop and simulation year. Once the model had abstracted water for irrigation it was linked to an *irrigation* function that used the stored *crop area* value and converted the *irrigation abstraction* into a mm/day value using the following equation:

$$Irrigation = (Irrigation\ Abstraction / Crop\ Area) * 1000 \qquad (2\text{-}8)$$

2.2.7 Plant Growth Module

Each crop has a unique optimal water requirement that was represented in the model as crop specific sufficiency curves. These curves determined yield based on *WaterAvailable*$_{Crop}$, which was calculated as the sum of precipitation and irrigation water (Belcher et al., 2004). *Rain depth* was a graphical input (mm/day) based on values from Environment and Climate Change Canada (Government of Canada, 2015c). The *WaterAvailable*$_{Crop}$ flow used the following equation to provide the amount of water available to each crop in mm/day:

$$WaterAvailable_{Crop} = Rain\ Depth + Irrigation * fraction\ abstraction \quad (2\text{-}9)$$

See Equation 2-6 for the *fractionAbstraction*$_{Crop}$ converter equation. On average within the study area, there is some initial spring soil moisture associated with snowmelt, however for the purposes of this model soil moisture was recharged with precipitation and/or irrigation water. All other factors affecting growth, such as nitrogen and phosphorus levels, and pesticides were assumed to be applied at the optimal level such that water was the only limiting factor to crop yield. Irrigation amounts were optimized to provide the highest crop yield.

WaterAvailable$_{Crop}$ flowed into the stock, *AvailableWaterDepth*. This stock held the inflowing available water and used it to calculate *ActualYield*. Each crop had a unique optimal water requirement that was represented in the model as crop specific sufficiency curves, which determined yield based on water availability (Figure 2-3)(Belcher et al., 2004). The water sufficiency curves for each crop informed the *ActualYield* in combination with the *Max Yield* converter. *Max Yield* was constant for each crop and each simulation year.

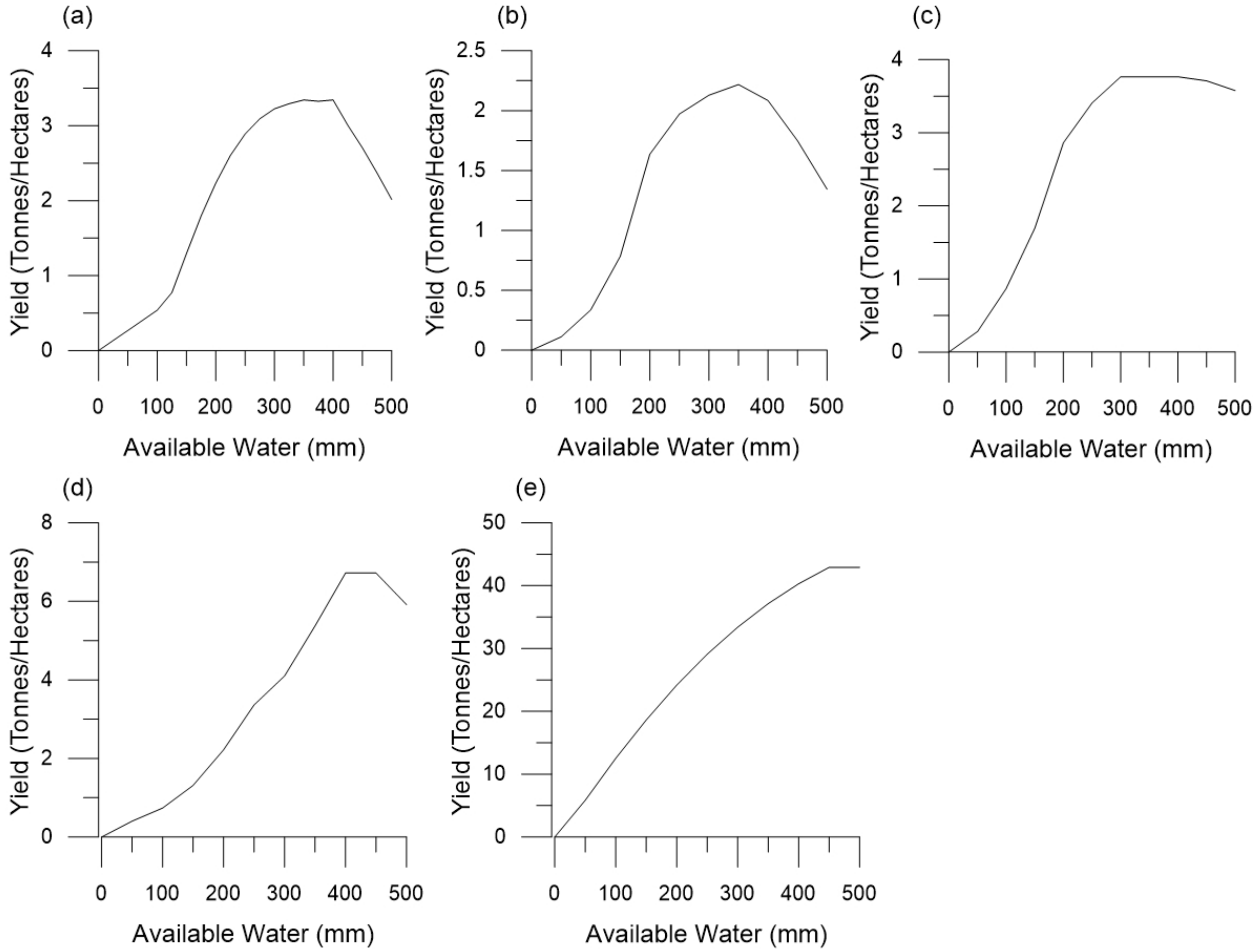

Figure 2-3. Water sufficiency curves for (a) wheat (b) canola (c) barley (d) alfalfa and (e) potato.

The equation for $ActualYield_{Crop}$ was:

$$ActualYield_{Crop} = Max\ Yield * Water\ Sufficiency\ Curve * 10{,}000 \qquad (2\text{-}10)$$

which provided the actual yield for each crop in tonnes/m^2. The $ActualYield_{Crop}$ converter then created a feedback to the converter, $Switch_{Crop}$ (refer to Equation 2-7). Irrigation was triggered when available water dropped below the level that provides 80% of optimal yield. $ActualYield_{Crop}$ was also used to estimate landscape level gross revenue. The formula for the $GrossRevenue_{Crop}$ converter was:

$$GrossRevenue_{Crop} = Actual\ Yield * Price * Crop\ Area * Fraction\ Crop\ Area/10{,}000 \qquad (2\text{-}11)$$

Crop prices were assumed to be fixed throughout the simulations and were from the Government of Manitoba estimated crop production costs for 2015 (Government of Manitoba, 2015a). Commodity prices for earlier years were not available, thus the 2015 prices were applied to all scenarios. The resultant gross revenues for each crop were used in combination with crop production costs and input costs to determine the net economic revenue under irrigation.

2.2.8 Economic Module

Landscape scale gross revenue was exported from the simulation model and input into Microsoft EXCEL to calculate landscape scale net revenue. Average production costs for the crop area were set at $534.93/hectare for all land within the study area. The production costs were based on the average (per/hectare) production costs for each of the four crops used in the study which were then weighted to reflect the proportion of each crop in the study area. Production costs were subtracted from gross revenue (Government of Manitoba, 2015a). Seed and treatment, fertilizer, fungicide, herbicide, and insecticide application along with fuel, machinery operation, lease, land taxes and interest costs were included in the above production cost. Average insurance costs for the four crops within the study site were set at $42.57/hectare and were included in the total production costs. Input costs, including reservoir and irrigation installation and upkeep costs as well as operating costs associated with each crop type, were constant for all STELLA simulations. Irrigation costs were averaged over the cropped land area ($/hectare). For simulations that did not include the reservoir and associated infrastructure, net revenue was calculated by subtracting production costs from gross crop revenue.

2.2.8.1 Reservoir costs

According to the LSRCD in which Pelly's Lake is situated, the total cost of converting the lake to a reservoir was $551,288. A 5.125% interest rate was applied to this value for a twenty year time horizon, the typical serviceable life of reservoir infrastructure, to estimate the total cost of installation with accrued interest (Waelti and Spuhler, 2012). The interest rate of 5.125% represented the current lending rate available to farmers through Manitoba Agriculture Services Corporation (MASC) for twenty year terms (MASC, 2016). Expected yearly maintenance of the dike system was accounted for by applying 2% of the installation cost to the final cost (Dion and McCandless, 2013). The final adjusted cost of the reservoir was divided by twenty to provide an annualized cost for reservoir development which was estimated to be $55,818/year ($8.33/hectare of irrigated crop land/year).

2.2.8.2 Irrigation costs

Price estimates for a centre-pivot sprinkler installation were from a report outlining the cost of irrigation infrastructure in Alberta (Grinder, 2000). Irrigation is less developed in

Manitoba in comparison to Alberta; thus there were no appropriate values for irrigation costs in Manitoba. A one-time installation cost of $1,500 per hectare was used to represent the average cost of installation of a typical centre-pivot sprinkler system (Grinder, 2000). These systems are twice the cost of surface or gravity flow irrigation systems, however they have grown in popularity due to their water efficiency and reduced need for labour. In Manitoba, these are the most commonly used irrigation systems (Gaia Consulting Limited, 2007). The per hectare cost of irrigation installation was multiplied by the crop area of Pelly's Lake watershed, amortized over 20 years at an interest of 5.125%, and then divided by 20 to give an annualized cost for the installation of irrigation, $1,017,208 ($151.88/hectare of irrigated cropland/year) (MASC, 2016). The cost of irrigation was assumed to capture any additional farm expenses that would be required during regular use such as increases in labour and equipment maintenance. It was assumed that farmers were responsible for the costs of reservoir establishment and irrigation infrastructure installation. Thus, net revenue for irrigated crops was calculated by subtracting operating costs and annualized costs associated with the reservoir and irrigation infrastructure from gross revenue.

2.2.8.3 Secondary benefits

Benefits in this section were divided into two calculation categories: actual realized values and ecosystem goods and services. Actual realized values were calculated for biomass production via cattail harvest and subsequent carbon offset credits. Both values represent revenue a farmer can receive in the current market for cattail harvest. The ecosystem goods and services, free benefits an ecosystem provides to humans, were estimated for the additional benefits of cattail harvest and the retention basin itself. These benefits included nitrogen and phosphorus capture and removal, an average global social cost of carbon credit production, and avoided downstream flood damages.

Biomass Production

The value of retention ponds used for biomass production was calculated using monetary values from a report published by IISD (Dion and McCandless, 2013). The report estimated the gross value of cattail production at $50.00/tonne. Grosshans (2013) found that the cost of harvest, custom bailing, custom field moving and hauling, repairs, and maintenance totalled $34.41/tonne. Therefore, the net value of dry cattail biomass was estimated to be $16.59/tonne (Dion and McCandless, 2013). Total harvestable cattail area (the surface area of the lake) was multiplied by the dry biomass cattails produce, 15 tonnes/hectare, to provide a total cattail biomass of 1,815 tonnes. Total cattail biomass multiplied by the cattail production value produced the actual realized value of cattail production at Pelly's Lake (Dion and McCandless, 2013).

Carbon Credits

Another benefit of producing and harvesting cattails is carbon credit production (Dion and McCandless, 2013). The social costs of carbon dioxide equivalent emissions were calculated by Clarkson and Deyes (2002) with the lower value estimate adjusted for 2016 CAD dollars equalling $64.00/tonne of carbon dioxide equivalent. The average cost of carbon dioxide damages to the atmosphere was calculated by the IPCC in 2005 to be $63.00/tonne (price adjusted for 2016 CAD dollars) (IPCC, 2007b; S. J. Wilson, 2008). The most recent IPCC report did not publish an updated average cost of carbon dioxide emissions due to the wide variance in economic costs based on mitigation strategies and availability of technology (IPCC, 2014). Studies in Canada have utilized both above estimates in valuing natural capital (Kennedy and Wilson, 2009; S. J. Wilson, 2008). An average value between the two studies of $63.50/tonne of carbon dioxide equivalent ($235.19/tonne of carbon) was set as the carbon credit value in this study. One tonne of dry cattail biomass yields 1.05 tonnes of carbon dioxide equivalent (Dion and McCandless, 2013; Grosshans et al., 2012a). Therefore, the total cattail biomass production at Pelly's Lake was estimated to be 1,906 tonnes of carbon dioxide equivalent. This value multiplied by the monetary value of carbon credits ($63.50/tonne) provided the total social carbon credit value from cattail harvest at Pelly's Lake (Dion and McCandless, 2013). While this value reflected the global social costs of carbon and potential value with improved carbon policies, the current voluntary offset market in Manitoba is providing a carbon credit of $25.00 (Manitoba Liquor and Lotteries Corporation, 2016) in support of cattail harvest for biomass production. Subsequently, two values for carbon offset from cattail harvest were calculated. An ecosystem goods and services value of carbon offset from cattail harvest at Pelly's Lake and an actual realized value of carbon offset using $25.00/tonne of carbon dioxide equivalent.

The retention basin itself is also sequestering carbon. Research by Badiou et al. (2011) on the Canadian Prairies estimated wetland restoration can provide a net sequestration rate of 3.25 tonnes of carbon dioxide equivalent/hectare/year. This value was multiplied by the surface area of Pelly's Lake and the monetary social value of carbon dioxide equivalent credits (63.50/tonne) to determine the yearly value of carbon sequestration by the retention basin.

Reduced eutrophication

Retention basins reduce downstream eutrophication by capturing sedimentation and nutrients, most importantly phosphorus and nitrogen. In 2004, phosphorus removal by waste water treatment plants in British Columbia ranged from $22.00 - $61.00/kg of phosphorus (Olewiler, 2004; S. J. Wilson, 2008). Adjusted for 2016 prices, the average price of phosphorus removal is $51.00/kg of phosphorus. This is in line with calculations by Sohngen et al. (2015) who estimated an average cost of $57.00/kg to reduce phosphorus at the watershed outlet. Sohgnen et al. (2015) also reported the Ohio, U.S., 2013 cost of removing phosphorus from waste water plants ranged between $17.00 to $90.00/kg. This value averaged, converted to Canadian dollars, and adjusted for 2016 prices becomes $71.66/kg of phosphorus. The three averaged prices for phosphorus removal were averaged for a value of $60.00/kg of phosphorus. Wetlands absorption of phosphorus depends on its size, plants, soil, and type. According to Olewiler (2004), 80 to 770 kg/ha/year of phosphorus can be removed by a wetland. The low end estimate was multiplied by the area of Pelly's Lake at $60.00/kg of phosphorus for the estimated value of phosphorus removal at the study site.

Wetlands also remove 350 to 32,000 kg/hectare of nitrogen per year (Olewiler, 2004; S. J. Wilson, 2008). Collins and Gillies (2014) estimated the cost of nitrogen removal from constructed wetlands to be $36.34/kg, adjusted for CAD 2016 dollars. The average cost of nitrogen removal from wastewater treatment plants in the US was calculated to be $140.10/kg, adjusted for 2016 CAD dollars (Collins and Gillies, 2014). Olewiler (2004) cited the average nitrogen removal costs in British Columbia, adjusted for inflation, to be $7.45/kg. As the range between values was so large, Collins and Gillies (2014) moderate estimate for constructed wetlands was used for this study. This cost was multiplied by the area of Pelly's Lake and the estimated amount of nitrogen removed, the conservative estimate of 350 kg/hectare/year, for the monetized impact of nitrogen removal at the study site.

Cattail biomass from Pelly's Lake also captures nitrogen and phosphorus. Cattails store these nutrients in their root zone as well as their organic and sediment layers. Harvesting the above ground portion of cattails can remove 20 to 60 kg of captured phosphorus/hectare from the ecosystem (Grosshans et al., 2014). The low end estimate of 20 kg/hectare was multiplied by the surface area of Pelly's Lake and the cost of removing phosphorus from cattails ($60.00/tonne) for the monetized impact of phosphorus removal from cattails. Cattail harvest also removes captured nitrogen from the ecosystem, as cattails capture up to 160 kg of nitrogen/hectare (Grosshans et al., 2014). The surface area of Pelly's Lake multiplied by 160 kg of nitrogen/hectare and the cost of removing nitrogen from cattails provided the monetized impact of nitrogen removal from cattails at the study site. Phosphorus and nitrogen removal were calculated separately for the retention basin and cattail harvest. This was due to the retention basin itself capturing nitrogen and phosphorus in the soil and lower two-thirds of unharvested cattail, and the cattail harvest removing captured nitrogen and phosphorus from the upper one-third portion of the cattail plant.

Flood water regulation

Other studies have also estimated the value retention ponds provide reducing downstream flooding damages. A report prepared by Schuyt and Brander (2004) calculated the median wetland economic value of flood control globally to be $464.00/hectare/year (US dollars, 2000 prices). Adjusted for inflation and converted to CAD dollars, flood control by wetlands provides $840.00/hectare/year. Brander, Brouwer, and Wagtendonk (2013) performed a meta-analysis of economic valuations of the regulating services provided by wetlands in agricultural landscapes. Their study determined the median value of flood control by wetlands to be $427.00/hectare/year (in US dollars, 2007 prices). Adjusted for inflation and converted to CAD dollars, flood control from wetlands provides $642.58/hectare/year. Estimates of flood control values were in most studies calculated based on avoided damage costs, and some studies estimated the cost of constructed flood control measures in place of wetlands (Brander et al., 2013; Schuyt and Brander, 2004). It was assumed these values considered more than road and culvert damages. The average value of $741.30/hectare/year was calculated for the surface area of the lake. This value was calculated for the study site along with the estimate from the RM of Stanley (2000), discussed below, to provide an estimated range in price for avoided flood damage costs.

Infrastructure Damage Mitigation

Retention basins aid in regulating flood waters, protecting against downstream infrastructure damages and increased sedimentation (Wilson, 2008). A report published by the RM of Stanley Soil Management Association (Stanley Soil Management Association, 2000) indicated how much yearly damage occurred to culverts and roads in the study watershed before a small dam network was installed. The average annual damage was estimated at $31,000 ($1.52/hectare). While the report did not indicate the reduction in damages after the small dam network was installed, they assumed the network would reduce damages in the order of 25%. This reduction would provide a savings of $0.38/hectare. The Stanley watershed is 20,390 hectares compared to the study watershed and adjacent downstream watershed area of 27,700 hectares and has similar land use parameters. This allowed for damages values to be transferred to the study watershed which provided a minimal estimate of damages to culverts and roads. Damage values from the report were adjusted for 2016 prices. Once the adjusted average annual damage was calculated per hectare, it was applied to the study watershed and adjacent downstream watershed area for a total annual damage reduction value provided by retention pond installation.

2.2.9 Sensitivity Analysis

Several sensitivity analyses were performed to determine the impact of infrastructure price, crop price, initial reservoir volume, maximum daily irrigation water volume, and the gap between actual and optimal yield, on net revenue. A sensitivity analysis was performed on reservoir and irrigation costs under four scenarios: 10% decrease, 5% decrease, 5% increase, and 10% increase in infrastructure costs. Crop prices were increased and decreased 10%, 25%, and 50% on both irrigated and non-irrigated crops. A sensitivity analysis was performed to determine whether the initial water volume available in the reservoir impacted gross revenue. The six scenarios analyzed were: 1) 10% increase, 2) 10% decrease, 3) 25% increase, 4) 25% decrease, 5) 50% increase, and 6) 50% decrease of reservoir volume.

The next sensitivity analysis varied the maximum daily irrigation water volume available for withdrawal. Seven scenarios were performed with maximum daily water volumes adjusted in increments of 10,000 m^3 from the maximum daily water volume of 15,000 m^3: 1) 5,000 m^3 2) 25,000 m^3, 3) 35,000 m^3, 4) 45,000 m^3, 5) 55,000 m^3, 6) 65,000 m^3, and 7) 75,000 m^3. The last sensitivity analysis was performed on the gap between actual and optimum yield, a value used to determine whether irrigation application is required. Irrigation was triggered when available water dropped below the level that provided 80% of optimal yield. The gap was varied in increments of ten percent, with four scenarios: 60%, 70%, 90%, and 100%, triggering irrigation when available water dropped below the level that provided that percentage of optimal yield.

2.2.10 Model Assessment

In addition to the sensitivity analyses, a more formal model evaluation was performed to ensure the newly developed modelling system was performing as expected. Sterman (2000) summarized the specific tests researchers use for improving system dynamic model performance and provided a detailed explanation of each test. Appropriate tests and questions focusing on the physical science components of model assessment, as outlined in Sterman (2000), were addressed in Table 2-2.

Table 2-2. Tests for assessment of dynamic models. Adapted from Sterman (2000).

Test	Purpose of Test	Results
1. Boundary Adequacy	Are the important concepts for addressing the problem endogenous to the model?	As suggested by Sterman (2000) stock and flow maps were used to ensure important concepts for addressing the problem were endogenous to the model. The stock flow diagram was then divided into subsystem components to highlight feedback loops (Figure 2-2). An inspection of model equation accuracy was also performed.
	Does the behavior of the model change significantly when boundary assumptions are relaxed?	The main boundaries of the model were the watershed area and reservoir volume. When these boundaries were increased, the model behaved as expected.
	Do the policy recommendations change when the model boundary is extended?	The model boundary was not extended as this is not within the scope of this research. However, the focus of future work is to extend the model boundary from the local scale to a regional scale.
2. Structure Assessment	Is the model structure consistent with relevant descriptive knowledge of the system?	Yes, a stock flow diagram was used to mimic real life situations as closely as possible.
	Is the level of aggregation appropriate?	Yes, the model assumed agricultural activities are owned primarily by one producer as is the case at Pelly's Lake. Expert opinion was attained from Richard Grosshans with the International Institute of Sustainable Development (IISD) who helped in the design of Pelly's Lake, our study site. Dr. Grosshans had a chance to review and provide feedback on our model. Consultation on the model was also attained from Dr. Benoy with the International Joint Commission who is an expert on the Manitoba region of the Prairies

		including the area's hydrology. Dr. Grosshans and Dr. Glenn Benoy felt the model was suitable for answering the research objectives and did not suggest changes or improvements were required.
	Does the model conform to basic physical laws such as conservation laws?	Yes, we used established discharge equations for flow and drawdown of the reservoir. Established methods were used to determine rain runoff and to describe plant growth. On the economic side of the model, traditional approaches for analyzing revenue were used.
3. Dimensional Consistency	Is each equation dimensionally consistent without the use of parameters having no real world meaning?	Yes, please refer to Section 2.1 for a full description of the equations used within the model. The model was based on established equations, parameters, and engineering methods. All dimensions within the model were real, with no scaling up or down. As true dimensions were used along with established methods, we do not anticipate any dimensional inconsistencies.
4. Parameter Assessment	Are the parameter values consistent with relevant descriptive and numerical knowledge of the system?	Parameters were adopted from the literature on traditional agricultural engineering practice.
	Do all parameters have real world counterparts?	Yes, parameters have real world counterparts.
5. Extreme Conditions	Does each equation make sense even when its inputs take on extreme values? Does the model respond plausibly when subjected to extreme policies, shocks, and parameters?	Extreme values were input for 1) initial reservoir volume, inflow, and rain, 2) crop prices, and 3) maximum crop yield. For each of the three scenarios above, the values were first adjusted to equal zero. Next, the values were adjusted to represent an extremely large value. All normal parameter values can be found in Table 2-1. Initial reservoir volume, inflow, and rain being set to zero for the duration of the simulation period had the expected result. Gross revenue for all crops equaled zero, as there was no water to allow for plant growth. The reservoir also remained empty. To model extreme values, initial reservoir volume was set at 10,000,000 m^3, inflow at 1,000,000 m^3/day, rain depth at 100 mm/day, and when irrigation was applied, maximum

		irrigation abstraction was set at 1,000,000 m^3/day. Actual yield in this scenario did not reach optimal yield for any of the four crops as expected. Gross revenue was subsequently slightly lower than under normal conditions. The reservoir drained initially to its full capacity and maintained that level with constant outflow. When irrigation was applied, the reservoir level was lower due to the abstractions. Gross revenue remained the same as no additional water was needed for maximum crop growth. All responses were as expected. Crop prices set at zero for the simulation period, both with and without irrigation also had the expected results. Crop yield was increasing, however gross revenue remained at zero. Crop prices were then set at a very large value of $10,000/tonne for each crop. As expected, this resulted in a substantial increase to gross revenue. When irrigation was applied at normal levels, gross revenue incrementally increased also as expected. Maximum crop yields set at zero for the simulation period, with and without irrigation resulted in no crop yield or crop revenue as expected. To test maximum crop yield with a very large value, all maximum crop yields were set at 10 tonnes/m^2. As expected, crop yield increased substantially resulting in increased gross revenue with and without irrigation.
6. Integration Error	Are the results sensitive to the choice of time step or numerical integration method?	The results were not sensitive to the choice of time step or numerical integration method. The analysis was run with three different integration methods: Euler's Method, Runge-Kutta 2, and Runge-Kutta 4. All methods resulted in the same response. The time step was reported every six hours initially. The time step was altered to report every 24 hours. There was no change in the model output when the time step was adjusted.
7. Behavior Reproduction	Does the model reproduce the behavior or interest in	The MESH hydrologic model simulated discharge was compared to observed discharge at the study site with an NSE of 0.73, an MSE

	the system (qualitatively and quantitatively)?	of 5.45, and a br^2 of 0.58. These results indicated a good fit between the MESH discharge simulations and observed discharge for the study site (Krause et al., 2005; Nash and Sutcliffe, 1970; Yapo et al., 1996) The RO model adequately simulated discharge compared to observed discharge at the study site with an r^2 value of 0.533, NSE of 0.533, and br^2 of 0.502. The SCS-CN model performance was good with an r^2 of 0.743, NSE of 0.736, and br^2 of 0.682. When the performance of the RO and SCS-CN method were combined and compared to the MESH model the two models performed well and had similar performance evaluations.
	Do the frequencies and phase relationships among the variables match the data?	Output was set on a daily basis as input values were mostly on a daily time step. Economic values were yearly; however daily output was used to match with the physical parameters.
8. Behavior Anomaly	Do anomalous behaviors result when assumptions of the model are changed or deleted?	No anomalous behaviors were observed.
9. Family Member	Can the model generate the behavior observed in other instances of the same system?	This question is out of the scope of this research, but is a focus of future work.
10. Surprise Behavior	Does the model generate previously unobserved or unrecognized behavior?	None were observed.
	Does the model successfully anticipate the response of the system to novel conditions?	Fluctuations to crop yield in very wet and dry years were as expected.
11. Sensitivity Analysis	Numerical sensitivity: Do the numerical values change significantly… Behavioral sensitivity: Do the modes of behavior generated by the model change significantly… Policy sensitivity: Do the policy implications change significantly… when assumptions about	Sensitivity analyses were performed. Refer to Chapter 3 for results.

	parameters, boundary, and aggregation are varied over the plausible range of uncertainty?	
12. System Improvement	Did the modeling process help change the system for the better?	The modeling process helped us to better define our feedback loop. Our original model did not incorporate a feedback loop.

2.2.11 Summary

A system dynamics model approach was introduced as the choice methodology for developing a modelling system capable of combining the various components of this study on a common spatial and temporal scale. The software, STELLA, was introduced as the platform for developing the modelling system. Five modules were created to address the research objectives of this study: hydrologic, reservoir, irrigation, plant growth, and economic. Each module was explained in terms of stocks and flows with a detailed description of parameters and equations used. A description of the sensitivity analyses performed and a formal model evaluation concluded this section. Two hydrologic models providing input for the hydrologic module will be detailed in the next section. Climate change data selection and application appropriate for answering objective three, the economic benefits of retention systems under future climate change, will be addressed in the final section of this chapter.

2.3 Hydrologic Input

2.3.1 Empirical Modeling

2.3.1.1 Introduction

In order to address the objectives outlined for this research, a rainfall-runoff model was used. A popular empirical method for determining rainfall-runoff, the Soil Conservation Service Curve Number (SCS-CN) method, was chosen due to its ease of use as well as its established ability to simulate runoff for a variety of climatic and topographic conditions (King et al., 1999; Singh et al., 2013; Soulis and Valiantzas, 2012; Viji et al., 2015; Zhan and Huang, 2004). The method is used for small watersheds to compute surface runoff from rainfall events by engineers, hydrologists, and watershed managers (Singh et al., 2013; Soulis and Valiantzas, 2012). Simulations run with simpler models such as the SCS-CN method have been shown to provide similar or better simulation data when compared to more complex physical models (King et al., 1999). Physical models have a theoretical basis and utilize measurable parameters which can yield precise predictions (King et al., 1999; Viji et al., 2015). However, physical models require substantive expertise, time, and data to run (Viji et al., 2015). Additionally, empirical relationships are often used within the more complex physical hydrologic model to estimate runoff (King et al., 1999; Singh et al., 2013). Use of an empirical model for this research allowed for the calculation of water storage capacity and subsequent water availability within a surface water retention system at Pelly's Lake, Manitoba. Further motivation in choosing the SCS-CN method was in its ability to provide easy regionalization to other catchments. This allows for future work in modeling several retention basins to consider the economic and environmental opportunities of a retention basin network. Climate change could also be linked within the SCS-CN method due to the inclusion of precipitation amounts. This enabled the model to determine water storage changes for present and future climate scenarios.

2.3.1.2 Hydrologic Model

The SCS-CN method is an established simple technique for estimating runoff volume from rainfall events (King et al., 1999; Singh et al., 2013; Soulis and Valiantzas, 2012; Viji et al., 2015). For a detailed description see Chapter 10 in the Hydrology National Engineering Handbook (Group, 2004). The runoff equation is:

$$Q = \frac{(P - I_a S)^2}{(P - I_a + S)} \; for\ P > I_a$$
$$Q = 0 \; for\ P \leq I_a \tag{2-12}$$

Where Q is the total runoff, P is precipitation, I_a is the initial abstraction, and S is maximum potential retention. It is assumed that I_a is a fraction of the potential maximum retention.

$$I_a = \lambda S \tag{2-13}$$

During SCS experimentation it was found that $I_a = 0.2(S)$, but remains an adjustable parameter of the method. Substituting $I_a = 0.2$ into Equation 2-12 you get:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \; for\ P > I_a \tag{2-14}$$

Potential maximum storage in the basin, S, is found in SI units (S in mm) via:

$$S = \frac{25400}{CN} - 254 \tag{2-15}$$

where CN is the curve number. Curve numbers are determined based on soil type, vegetation, land use, cultivation practices, and antecedent moisture conditions.

Research by Soulis and Valiantzas (2012) illustrated that a two-CN method can more accurately predict runoff when compared to the original one CN method outlined above. Thus for this research, a two CN method was adopted. Two CN values were determined for the watershed for the two largest homogeneous sub-areas with $CN_a > CN_b$. The area fraction of the Pelly's Lake watershed, a, for the largest landcover type was 0.78, representing agricultural land. A weighted average of agricultural land cover was calculated using land cover types outlined in CN value tables for CN_a (NRCS, 1986). The second largest landcover within the watershed was forest. A weighted average of forest land cover types outlined in the CN value tables produced CN_b (NRCS, 1986). The area fraction of forest landcover became (1-a) (Soulis and Valiantzas, 2012). Using the two-CN method, Equation 2-14 became:

$$Q = 0 \; for \; P < \lambda S_a \tag{2-16}$$

$$Q = a \frac{(P - \lambda S_a)^2}{[P + (1 - \lambda) S_a]} \; for \; \lambda S_a \leq P < \lambda S_b \tag{2-17}$$

$$Q = a \frac{(P - \lambda S_a)^2}{[P + (1 - \lambda) S_a]} + (1 - a) \frac{(P - \lambda S_b)^2}{[P + (1 - \lambda) S_b]} \; for \; P \geq \lambda S_b \tag{2-18}$$

Where Q is the total runoff (mm), P is precipitation (mm), a is the fraction of the watershed assigned to CN_a, and λ is a constant typically set to 0.2 or 0.05. S_a and S_b are maximum potential retention values which correspond to CN_a and CN_b respectively and were calculated using Equation 2-15 (Soulis and Valiantzas, 2012). The weighted CN values, calculated using the CN value tables, assumed average antecedent moisture conditions (antecedent moisture condition II). A five-day antecedent rainfall calculation was used to determine the CN values for antecedent moisture condition I and III (Table 2-3). The precipitation sum for the five previous days was calculated and based on the precipitation amount. The CN value for the watershed was adjusted accordingly (NRCS, 1986).

Table 2-3. Rainfall limits for estimating antecedent moisture conditions. Adapted from Thompson (1999).

Antecedent moisture condition class	5-day total antecedent rainfall (mm)	
	Dormant Season	Growing season
I	< 12.7	<35.56
II	12.7 – 27.94	35.56 – 53.34
III	> 27.94	> 53.34

It was found that the SCS-CN Method did not fully account for spring melt runoff when model results were compared to observed runoff values for the study watershed. To account for this, the Antecedent Precipitation Index (API) Method was added to the model. Within Manitoba, API and winter precipitation (WP) are well known to contribute to spring flooding events (Warkentin, 1999). API is a weighted basin precipitation from May to October representing soil moisture at freeze-up in the previous fall (Warkentin, 1999). The equation for calculating API is:

$$API = 0.30P_{OCT} + 0.25P_{SEPT} + 0.18P_{AUG} + 0.12P_{JUN} + 0.08P_{JUL} + 0.07P_{MAY} \quad (3\text{-}5)$$

where *P* is total precipitation (in mm) for each noted month. The total freshet runoff can be calculated as:

$$RO = C_1\,(API) + C_2\,(WP) + C_3\,(SR) + b \quad (3\text{-}6)$$

where *RO* is direct runoff (mm), *API* is the antecedent precipitation index (mm), *WP* is winter precipitation (mm) for November, December, January, February and March of a given winter, and *SR* is the spring rain during freshet (mm). C_1, C_2, and C_3 represent calibration coefficients. The variable *b* is an axis intercept which helps to increase the correlation R^2 as well as reflecting the reality of the distribution of points.

Simulated flow for the catchment area, converted to m^3/day, was calculated for May 1 – Sept 15 each year using the two CN method. The API method provided April simulated flow for each year. Multiplying the simulated runoff by the catchment area provided the initial reservoir volume each year. Baseflow was excluded in the empirical model due to limited data availability. Baseflow estimations added to the model were found to have no significant impact on results. Simulated flow and initial reservoir volume were input into the STELLA modelling system (Figure 2-2).

2.3.1.3 Model Setup

Climate data was acquired from the Government of Canada (2015c). Precipitation values were from four stations: St. Alphonse, MB, Holland, MB, Somerset, MB, and Rathwell, MB. Discharge data for calibration and validation was from Station Number O5OF010, Boyne River near Treherne (Government of Canada, 2014). Weighted CN values determined for the Pelly's Lake watershed were set at $CN_a = 79$ and $CN_b = 70$.

2.3.1.4 SCS-CN Calibration

To optimize model performance, the precipitation parameter was calibrated. Precipitation values were from one station (Holland, MB), averaged for three stations creating a triangle encompassing the watershed (St. Alphonse, MB, Cypress, MB, Rathwell, MB), and four stations encompassing the watershed (St. Alphonse, MB, Holland, MB, Somerset, MB, Rathwell, MB). Simulations were most accurate using the average of four stations encompassing the watershed.

CN values were also adjusted until the model predicted cumulative discharge values reasonably (Ouyang et al., 2010). Refer to Table 2-4 for parameter values after calibration. Measured and modeled values were compared in Figure 2-4, with the linear regression equation and R^2 value of 0.7537 noted. The coefficient of determination (R^2) describes the proportion of observed data explained by the model. A value of zero indicates no correlation between simulated and measured data while a value of 1 indicates the dispersion of the simulated data is equal to the measured data. Values above 0.5 are considered acceptable (Krause et al., 2005; Moriasi et al., 2007).

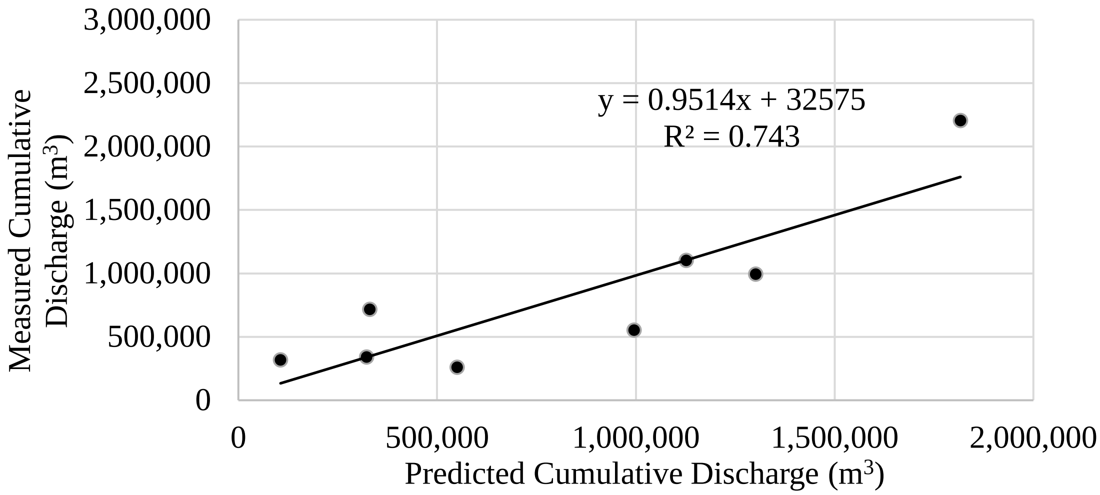

Figure 2-4. Comparison of measured and predicted cumulative discharge (June 30th) for the Boyne River near Treherne, MB (1985-1994).

Table 2-4. Calibrated input values for the SCS-CN method.

Parameter	Value	Reference
Curve number a, CN_a	Class I = 40 Class II = 61 Class III = 79	(NRCS, 1986; Soulis and Valiantzas, 2012; Thompson, 1999)
Curve number b, CN_b	Class I = 59 Class II = 76.5 Class III = 89	(NRCS, 1986; Soulis and Valiantzas, 2012; Thompson, 1999)
Area fraction of watershed, *a*	0.78	(Manitoba Government, 2014; Soulis and Valiantzas, 2012)
λ constant	0.065	(Soulis and Valiantzas, 2012)
Precipitation, *P*	Variable	(Government of Canada, 2015c)

2.3.1.5 2 API and WP Method

Spring runoff values calculated using the API Method required calibration of calibration coefficients C_1, C_2, C_3 and b included in the direct runoff (*RO*) equation. All other parameters were obtained using published measurements and did not require calibration. Calibration resulted in $C_1 = 0$ which meant API had no significant impact on results, $C_2 = 0.4$, $C_3 = 0.4$, and $b = -25$. Measured and modeled runoff values for April were compared in Figure 2-5 with the linear regression equation and R^2 value of .5106 noted.

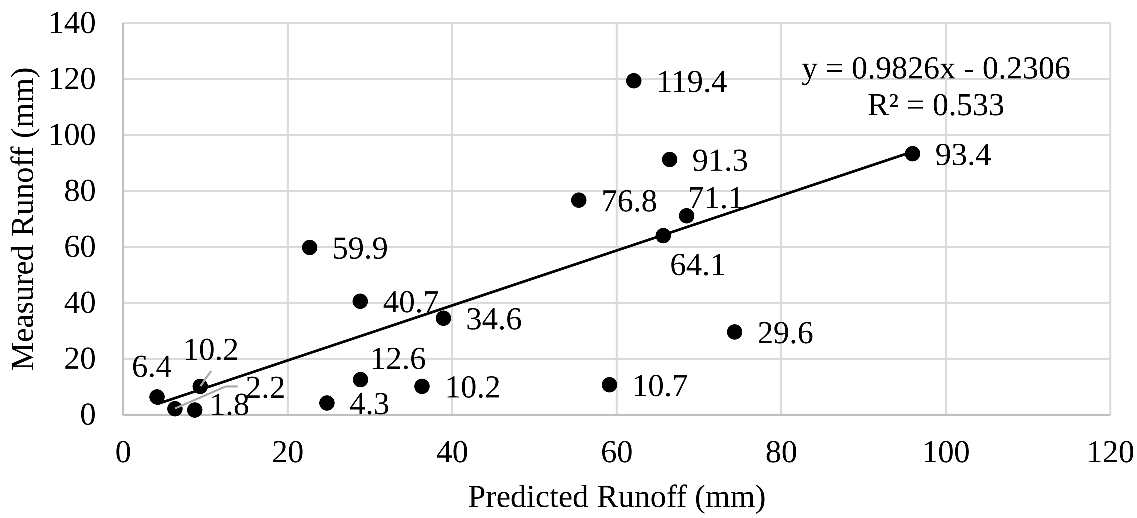

Figure 2-5. Comparison of predicted and measured cumulative runoff (April 30th) for the Boyne River near Treherne (1967-1984).

2.3.2 Physically Based Modeling

2.3.2.1 Introduction

Modélisation Environmentale Communautaire - Surface and Hydrology (MESH) served as the physical hydrologic model providing streamflow inputs into the reservoir and the initial reservoir volume from the spring freshet. The Environment and Climate Change Canada environmental modelling system MESH was used to model the hydrologic component of the target watershed. This distributed land surface model is commonly used in Canada for medium to large scale simulations (Pietroniro et al., 2007; Verseghy, 1991). Environment and Climate Change Canada uses MESH as part of an operational forecasting tool and the system is currently being used within research projects such as the Drought Research Initiative (DRI) (University of Saskatchewan, 2015). MESH is designed to simulate several hydrological processes: evaporation, snow accumulation and ablation, interception, interflow, infiltration, recharge, baseflow, and overland and channel routing processes (Kouwen et al., 1993; Mengistu and Spence, 2016). The model allows for streamflow to be simulated at any point within the watershed (Mengistu and Spence, 2016). This ability is a major advantage of a fully distributed model (Viji et al., 2015).

2.3.2.2 Hydrologic Model

MESH required multiple inputs to provide a complete distributed land surface model. The energy and water balance requirements for the model were determined utilizing the Canadian Land Surface Scheme (CLASS) 1 (Verseghy, 1991) and CLASS 2 (Verseghy et al., 1993). The physically based land surface model, CLASS 1, calculated heat and moisture transfer at the surface while CLASS 2 calculated energy and moisture fluxes at the canopy level (Verseghy, 1991; Verseghy et al., 1993). The algorithms used in CLASS 1 and 2 were run on each grouped response unit (GRU) independently (Kouwen et al., 1993; Mengistu and Spence, 2016). Precipitation data for MESH were from the Canadian precipitation analysis (CaPA) project which produces rainfall accumulations at a six hour time step and resolution of 15 km over North America in real-time (Mahfouf et al., 2007). Further required climatic data such as long wave and short wave radiation, humidity, pressure and wind speed were from the Global Environmental Multiscale (GEM) Model (Côté et al., 1998; Pietroniro et al., 2007). Routing of water within the study area was performed within the MESH model using a storage-routing technique which applied the continuity equation as outlined in Kouwen et al., (1993):

$$\frac{I_1+I_2}{2} - \frac{O_1+O_2}{2} = \frac{S_2-S_1}{\Delta t} \tag{3-11}$$

where $I_{1,2}$ represent inflow to the reach from overland flow, interflow, base flow, and channel flow (m^3/s), $O_{1,2}$ represent outflow from the reach (m^3/s), $S_{1,2}$ are storage in the reach (m^3), and Δt is the time step of the routing in seconds. Subscript 1 represents the beginning time step quantities and subscript 2 represents the ending time step quantities. The MESH model system is depicted in Figure 2-6. For a full description of the MESH model refer to Mekonnen et al. (2014). Daily discharge values and initial reservoir volume values from MESH were input into the model as represented in Figure 2-2, a stock-flow diagram of the modeling system within STELLA.

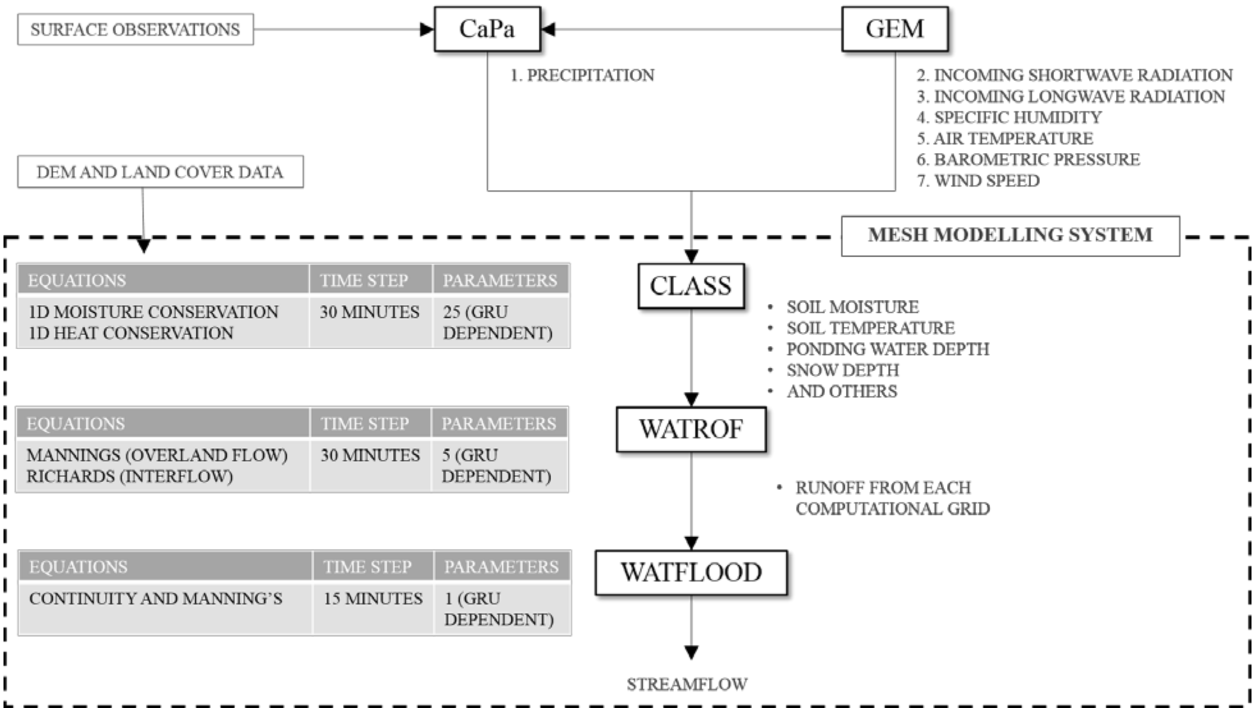

Figure 2-6. The MESH modelling system. Adapted from Mekonnen et al., (2014).

2.3.2.3 Modeling Data and Data Preprocessing

Topography for the study watershed was derived from a Canadian Digital Elevation Model (CDEM) with an average accuracy of 4.3 and spatial resolution of 0.75 (Government of Canada, 2016). Landcover data required as a spatial input into MESH was acquired from the Canada Centre for Mapping and Earth Observation (CCMEO) (Government of Canada, 2013). Landcover data was used to define GRUs within MESH. Soil and vegetation parameters were determined within MESH based on landcover type. Five land cover types were classified: Class 1) Forest, Class 2) Grasslands, Class 3) Cropland, Class 4) Urban, Class 5) Water. The watershed landcover consisted of 58% cropland, 11% grassland, 8% forest, 20% urban, and 3% water (Government of Manitoba, 2014c). Daily streamflow values were from station number O5OF011, Boyne River near Roseisle for use in calibration (Government of Canada, 2014).

2.3.2.4 Model Setup

A spin up period consisted of years 2011-2012. Access to streamflow data was only available for 2013 and 2014, thus 2013 was used as a calibration period and 2014 served as the validation period. The availability of streamflow observations in the study area were very limited resulting in the short time periods used for calibration and validation. This constraint on data availability affects modelling everywhere, including here in Canada.

Several relevant parameters were calibrated to produce acceptable streamflow simulations (Table 2-5). Simulated and observed streamflow for the calibration and validation period were compared in Figure 2-7. Performance evaluations are also included in Figure 2-7. The components precipitation, evaporation, runoff, and change in storage were examined within MESH to ensure inputs and outputs balanced the change in storage (Figure 2-8).

Table 2-5. Parameters with calibration ranges used in MESH calibration.

Calibrated parameter	Description	Calibration range
GRKF	Fraction of the saturated surface soil conductivity moving in the horizontal direction	0.0001 – 1
MANN	Manning's 'n'	0.001 – 1
KSROW	Saturated surface soil conductivity	0.0001 – 1.02
SANDF1	Percent content of sand	20 – 70
SANDF2	Percent content of sand	20 – 70
SANDF3	Percent content of sand	20 – 70
CLAYF1	Percent content of clay	10 – 30
CLAYF2	Percent content of clay	10 – 30
CLAYF3	Percent content of clay	10 – 30
WFR21	River channel roughness factor for channel routing	0.3 – 1
ZSNL	Minimum depth to consider 100% cover of snow on the ground surface	0.05 – 0.15
ZPLS	Maximum depth of liquid water allowed to be stored on the ground surface for snow-covered areas	0.05 – 0.15
ZPLG	Maximum depth of liquid allowed to be stored on the ground surface for snow-free areas	0.05 – 0.15

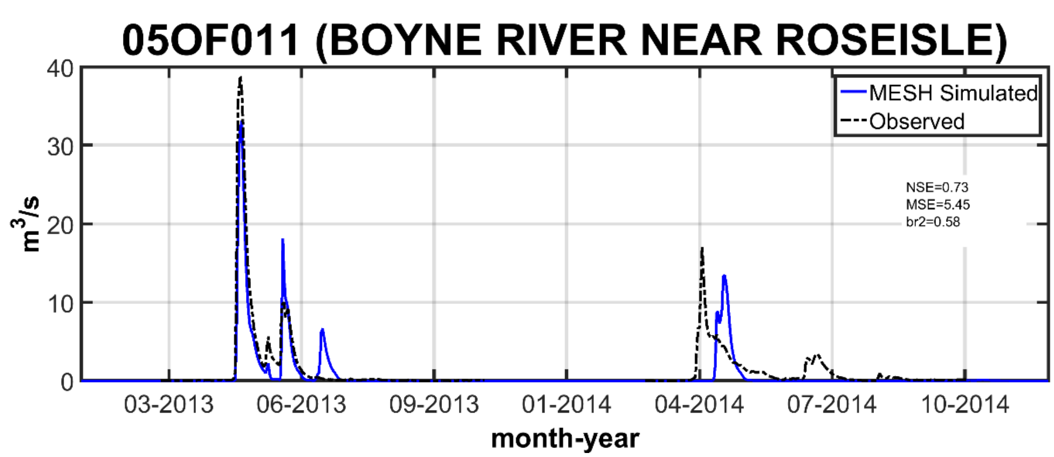

Figure 2-7. Comparison of MESH simulated and observed streamflow.

The Nash-Sutcliffe efficiency (NSE) statistic was used to determine how well the observed versus simulated data plot fit the 1:1 slope line. Values for NSE range between -∞ and 1.0. As the value approaches 1, the accuracy of the model increases with an NSE of 1 representing a perfect match between observed and modelled data. All NSE values ≤ 0 indicate mean observed values are better predictors than the modelled values (Moriasi et al., 2007; Nash and Sutcliffe, 1970). Moriasi et al. (2007) performed a literature review to obtain recommended statistical values for NSE. Satisfactory NSE values > 0.5 were typically considered satisfactory, with values >.80 considered efficient.

Mean squared error (MSE) was also used to quantify the error between simulated and observed datasets. Values for this criterion range from 0, perfect accuracy, to infinity and is widely used for hydrologic model calibration and evaluation (Gupta et al., 2009). The last performance evaluation calculated was the br^2 coefficient. This coefficient multiplies the slope of the regression line between observed and simulated data by the coefficient of determination, r^2, and treats missing values (Glavan and Pintar, 2012; Krause et al., 2005). Values close to 1 with r^2 indicates the dispersion of the prediction is close to the observation. However, systematic over and under predicting models will still result in a r^2 value close to 1. This is problematic as the result appears like a good fit between the model and observed data, but the model's predictions can still all be wrong. To correct this, one must consider r^2 in combination with the regression line gradient, b, in the formula:

$$br^2 = \begin{cases} |b| \quad r^2, & b \le 1 \\ |b|^{-1} r^2, & b > 1 \end{cases} \tag{3-11}$$

This formula corrects for under or over predicting models by quantifying them together (b) with their dynamics (r^2). A more comprehensive reflection of modeling performance is the result of the br^2 coefficient (Glavan and Pintar, 2012; Krause et al., 2005).

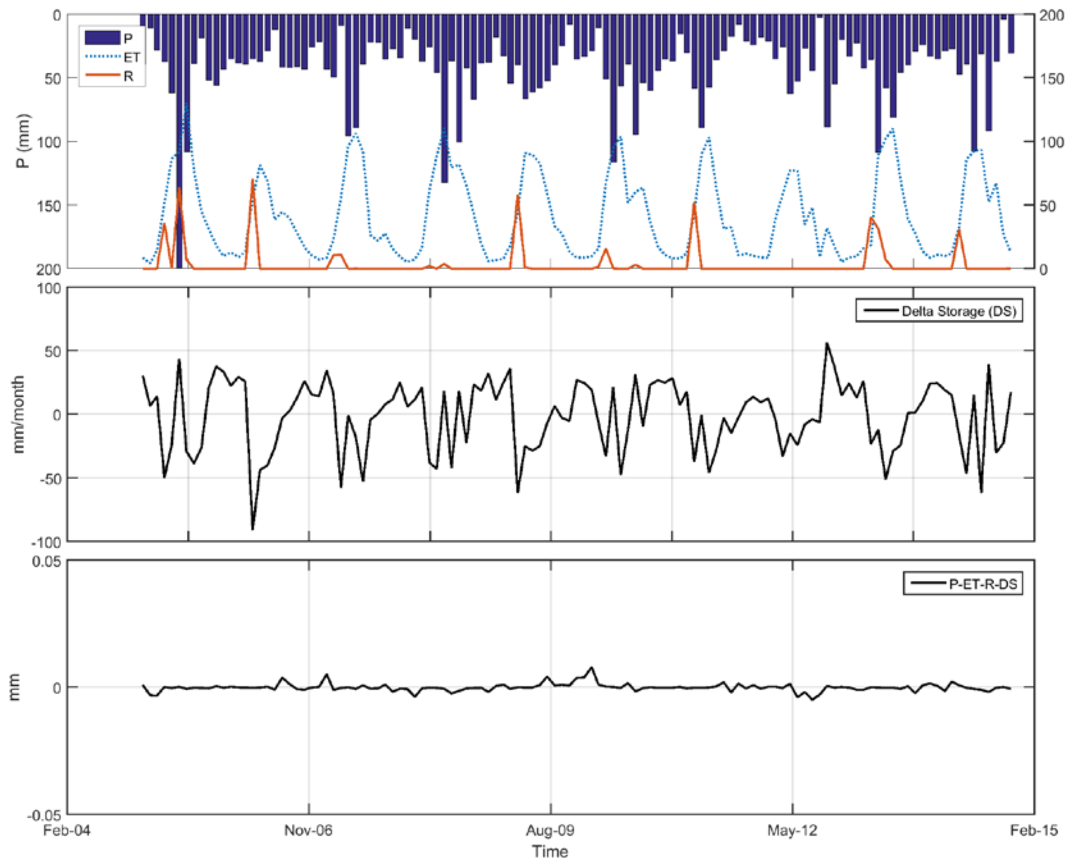

Figure 2-8. Water balance for Pelly's Lake, Manitoba showing precipitation (P), evapotranspiration (ET), runoff (R), and change in storage (DS) from 2005-2014.

2.3.2.5 Summary

This section introduced two differing hydrologic models used to generate initial reservoir volume and daily streamflow input values for the modeling system. The Runoff/SCS-CN (RO/SCS-CN) empirical model was chosen due to its ease of use and established capacity for simulating runoff from small watersheds with various climatic and topographic parameters. This method also allows for easy regionalization of the study to other catchments to consider the economic and environmental opportunities associated with a retention basin network. A physical model, MESH, was also used to simulate runoff. This model could also be used for regionalization of the study, but would require substantially more time and resources than the RO/SCS-CN method. The MESH model considers more hydrologic processes than the RO/SCS-CN model and subsequently could yield more precise streamflow outputs. Model setup was detailed for both models including calibration and validation measures.

2.4 Climate Change

2.4.1 Introduction

The last objective of this research was to explore the potential economic advantages associated with retention ponds under future climate conditions. Hydrologic inputs from future climate scenarios were thus required. The most advanced tools available today for simulating future climate are general circulation models (GCMs). These numerical models simulate global climate by incorporating the physical processes occurring in the atmosphere, cryosphere, ocean, and land surface globally. Increasing greenhouse gas concentrations can be modelled within GCMs to simulate present and future global climate systems responses (IPCC-TGICA, 2007; Trzaska and Schnarr, 2014; Farmer, 2015). GCMs can be applied at a global scale down to a continental scale with reasonably accurate simulations. However, decision makers often require future climate scenario information at a finer scale (Trzaska and Schnarr, 2014; Werner, 2011). Geographically and physically consistent regional climate change estimates required for impact analysis can be obtained from GCMs when used in combination with downscaling methods. Downscaling methods are required to increase model resolution as GCMs have a coarse horizontal resolution of 100-500 km (IPCC-TGICA, 2007b; Trzaska and Schnarr, 2014).

There are two categories of downscaling, statistical and dynamical, used to achieve resolution finer than 100 km and temporal scales less than a month. Statistical downscaling techniques have the capacity to provide high resolution future climate simulations at specific locations or regions. Statistical relationships are established between the climate features of the GCM and local climate characteristics. This method is easily applied and interpreted with limited resources and knowledge (IPCC-TGICA, 2007; Trzaska and Schnarr, 2014; Werner, 2011, Flato et al., 2013). However, it can be difficult to acquire accurate historical climate observations required for this method due to lack of availability (Trzaska and Schnarr, 2014). Another limitation of this method is that relationships developed between the historical and GCM climate features are assumed to be constant in the future (Trzaska and Schnarr, 2014). Dynamical downscaling utilizes a regional climate model (RCM) which includes coarse scale GCM outputs on atmospheric information along with additional climate data in the localized area allowing for higher resolution outputs between 20-50 km. Unlike statistical downscaling, this method requires extensive expertise for set up and understanding of the downscaled results (Trzaska and Schnarr, 2014, Flato et al., 2013). Dynamical and statistical downscaling methods can also be used in conjunction to increase resolution and improve output accuracy (Trzaska and Schnarr, 2014, Flato et al., 2013).

2.4.1.1 Uncertainty

Climate projections from GCMs as well as downscaled methods have several sources of uncertainty (IPCC-TGICA, 2007b; Trzaska and Schnarr, 2014). Future anthropogenic emission levels involve uncertainty. Models used for simulating future climate scenarios have uncertainties linked to imperfect representation of climate processes. Current understanding of climate conditions is imperfect leading to imperfect knowledge being fed into projections (IPCC-TGICA, 2007b; Trzaska and Schnarr, 2014). Finally, variability at the interannual and decadal level is difficult to represent accurately in long-term projections. However, this does not mean future climate projections are false, as uncertainty can be quantified (Trzaska and Schnarr, 2014). Multiple greenhouse gas emission scenarios are modeled to account for the uncertainty in future socio-economic and demographic conditions as well as technologic advancements. It is also recommended to use a multi-model ensemble approach when modeling future climate conditions. Each GCM and downscaling method has a unique set of parameters as initial conditions within the model. By using future climate scenario results for as many models as possible and producing a multi-model ensemble mean or median, a more probable future climate scenario can be determined. The spread in results between models illustrates the level of uncertainty in the obtained multi-model ensemble results (Charron, 2014; Trzaska and Schnarr, 2014; Werner, 2011).

2.4.1.2 Representative Concentration Pathways

Future emission scenarios are developed by the Intergovernmental Panel on Climate Change (IPCC). Climate experts from across the globe review the most recent and relevant information pertinent to understanding climate change to come up with recommendations for the scientific community and end users of climate change information. Emission scenarios are also determined from this information to reflect plausible future greenhouse gas levels, based on various socioeconomic, technological, demographic, policy and institutional assumptions (Intergovernmental Panel on Climate Change (IPCC), 2014; IPCC-TGICA, 2007b). The latest assessment report (AR5) includes four representative concentration pathways (RCPs) defined by their total radiative forcing pathway and level by 2100: RCP8.5, RCP6, RCP4.5, and RCP2.6. Total radiative forcing refers to cumulative GHG emissions by humans in Watts/m^2. Table 2-6 outlines the emissions scenario description for each RCP (IPCC, 2014). Greenhouse gas emissions from these four RCPs are input into GCMs and downscaled climate models to provide future climate scenarios under differing radiative forcing conditions.

Table 2-6. Representative concentration pathways (RCPs) overview.

RCP	Description
RCP2.6	Radiative forcing will peak at approximately 3 W/m^2 before 2100 and then levels will decline.
RCP4.5	Radiative forcing will stabilize at 4.5 W/m^2 after 2100.
RCP6	Radiative forcing will stabilize at 6 W/m^2 after 2100.
RCP8.5	Radiative forcing will rise resulting in 8.5W/m^2 in 2100.

2.4.2 Data Selection

Data selection depends on the specific requirements of each research question. Variables required for the study, the spatial scale under study, and the temporal resolution required shape the data selection process (IPCC-TGICA, 2007b). The amount of time available to produce results and the finances available come into consideration as well. Finally, the expertise of the researcher impacts the choice of downscaling method used when fine scale resolutions are required (Trzaska and Schnarr, 2014). For this research, future precipitation data was required at a fine resolution over the study site which could be easily input into the two hydrologic models. The modeling system could then provide projections of how water storage at Pelly's Lake would be affected by climate change.

Statistically downscaled climate data for the study area was acquired from the Pacific Climate Impacts Consortium (PCIC) for the present study (Pacific Climate Impacts Consortium (PCIC), 2014; Werner, 2011). Climate scenarios are available across Canada from PCIC. Data is produced at a gridded resolution of roughly 10 km or 300 arc-seconds for 1950-2100. Users can download three output variables on a daily time step: precipitation, minimum temperature, and maximum temperature (PCIC, 2014). Scenarios for all four RCPs are available and multi-model ensemble tables are provided to aid the researcher in climate model selection with the widest breadth of future climate simulations. Historical daily gridded climate data for Canada was used in combination with GCM projections from the Coupled Model Intercomparison Project Phase 5 (PCIC, 2014).

A model ensemble for Western North America containing 12 different models was provided by PCIC (2014). Due to constraints on time and resources, the model ensemble list was narrowed down to contain only four models for this study (Table 2-7). Of the two downscaling methods provided by PCIC (2014), Bias Corrected Spatial Disaggregation (BSCD) was chosen for this study due to its extensive application in previous hydrologic modelling research. Further description of the application of BSCD to PCIC scenarios can be found in Werner (2011). Three of the four RCPs were chosen for this study: RCP2.6, RCP4.5, and RCP8. These three RCPs provided two extreme scenarios and a median scenario. The exclusion of RCP6 was due to time constraints.

Table 2-7. Selected models used in multi-model ensemble of future climate scenarios.

Modeling Center	Institute ID	Model Name
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2
Meteorological Office Hadley Centre	MOHC	HadGEM2-ES
Max Planck Institute for Meteorology	MPI-M	MPI-ESM-LR
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-ESM2G

2.4.3 Data Application

Future climate conditions were modeled for two ten-year time periods, 2050-2059 and 2090-2099. This allowed for comparison between model results for the beginning of the century (2002-2014), the middle (2050-2059) and the end of this century (2090-2099). Outputs from the four chosen climate models and three RCPs were downloaded for the study area. As the downscaled models have a grid resolution of approximately 10 km, outputs were spatially constrained over the study area between latitudes 49°N to 50°N and longitudes 98°W to 97°W.

Model precipitation outputs were plotted from 1950-2100 for each scenario (Figure 2-9). Precipitation was divided between summer and winter to determine multi-model ensemble mean increment changes in precipitation for the two seasons. These plots indicated a consensus in future climate precipitation trends between the four different models, which increased confidence that the climate models were performing as desired. Confidence in the models abilities to simulate future climate conditions was further increased by the clear trends between models for each RCP. Outputs from the PCIC downscaled models support the findings published by Warren and Lemmon (2014) that precipitation is projected to increase for all seasons across Canada in the future. Future precipitation simulation outputs in the same report also indicated precipitation increases would be greater in the winter than the summer (Warren and Lemmon, 2014). PCIC future precipitation simulations all increased, with a larger increase in the winter (Table 2-8).

Precipitation outputs for the 2050s and 2090s were input into the empirical RO/SCS-CN model to provide the hydrologic input for the STELLA model. For the MESH hydrologic input, incremental change in precipitation from the RCP4.5 multi-model ensemble mean was applied to the 2005-2014 precipitation inputs (Table 2-8). All other parameters within the modeling system remained the same as for the present day simulations (2002-2014).

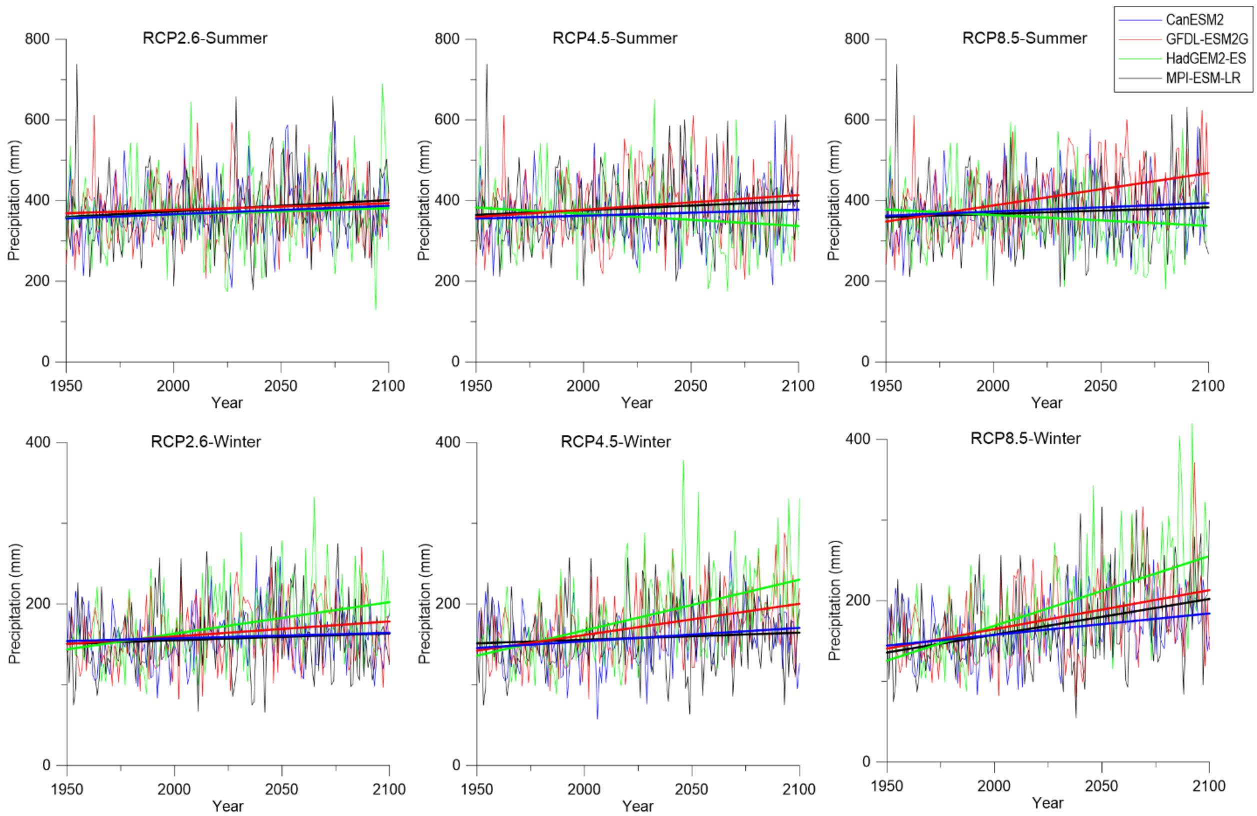

Figure 2-9. Multi-model ensembles for each RCP showing summer and winter precipitation with lines representing mean precipitation for each climate model. The spread between model simulations illustrates uncertainty.

Table 2-8. Precipitation totals and incremental increases between study periods based on the multi-model ensemble means for RCP4.5.

Decade	Season	Mean season precipitation total	Incremental increase
Summer precipitation			
2005-2014	May – October	371.9	
2050-2059	May – October	376.8	1.3%
2090-2091	May – October	381.2	2.5%
Winter precipitation			
2005-2014	November – April	162.7	
2050-2059	November – April	176.9	8.8%
2090-2091	November – April	189.6	16.6%

2.4.4 Summary

This section provided an introduction to climate change as the last objective of the study was to explore the economic advantages associated with retention ponds under future climatic conditions. Statistically downscaled climate data for the study area was acquired from PCIC. Future precipitation was input into the RO/SCS-CN empirical model to produce initial reservoir volume and daily streamflow input values for the future simulation periods. The incremental change in precipitation from the RCP4.5 multi-model ensemble mean, acquired from PCIC, was applied to the 2005-2014 precipitation inputs from MESH to produce hydrologic data for the future simulation periods. The next chapter begins by comparing the two hydrologic models performance. Results of each research objective are then presented and compared based on the method of hydrologic input used.

CHAPTER 3

RESULTS

Two hydrologic models used in providing initial reservoir volume and daily streamflow inputs to the modeling system were introduced in Chapter 2. The more simplistic empirical RO/SCS-CN hydrologic model and the more complex physical MESH hydrologic model. This chapter will detail each model's performance to determine which model produced more accurate runoff simulations. The modeling system sensitivity analysis results will also be detailed. The chapter will then detail the results of each objective, dividing results by the hydrologic model used in producing streamflow input. This will allow for further model performance comparison and also provide further substantiation to the analysis.

3.1 Physical and Empirical Based Modelling: A Comparison

Two hydrologic models applied to the study site provided hydrologic input for the modeling system. The RO/SCS-CN Method was pursued initially as a simple, proven way of determining discharge with minimal input variables (King et al., 1999). There remained a level of uncertainty in how well the model was capturing surface runoff and precipitation events due to the very simplicity of the model. A physical model could potentially provide more accurate results. Resources became available allowing for the study site to be modeled in the more complex MESH model. Due to the inclusion of multiple input variables and complex multiple hydrological processes in MESH, it was felt the results may prove more accurate to the surface runoff hydrology of the study area. Application of both models to the study site also allowed for model comparison to determine which model is more accurate.

Monthly simulations in MESH simulated observed runoff volumes well, but the timing of runoff events were off in some cases. Overall, with an NSE of 0.73, br^2 of 0.58, and MSE of 5.45 the model performed well (Figure 2-7). Cumulative runoff simulations for April 30th using the RO method generally followed the pattern of observed runoff volumes (Figure 3-1). However, the model did over and under simulate runoff volumes throughout the simulation period. An r^2 value of 0.533, NSE of 0.533, and br^2 of 0.502 confirm that the model is providing an adequate, but not good, representation of spring surface runoff.

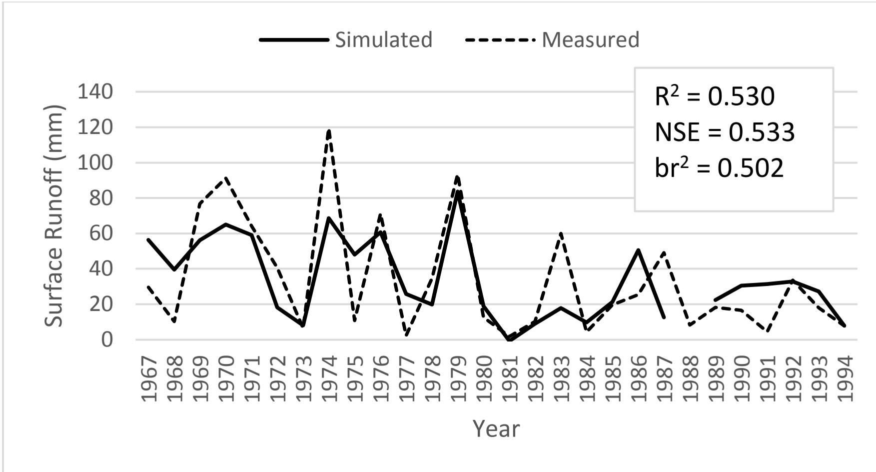

Figure 3-1. Simulated and measured yearly cumulative runoff for April 30th (1967-1994).

Cumulative discharge simulations using the SCS-CN method performed well, closely simulating observed discharge. Model performance was good with an r^2 of 0.743, NSE of 0.736, and br^2 of 0.682 (Refer to Figure 3-2). The year 1986 was removed from the series as the high observed cumulative discharge in that year was not captured by the model and subsequently skewed results.

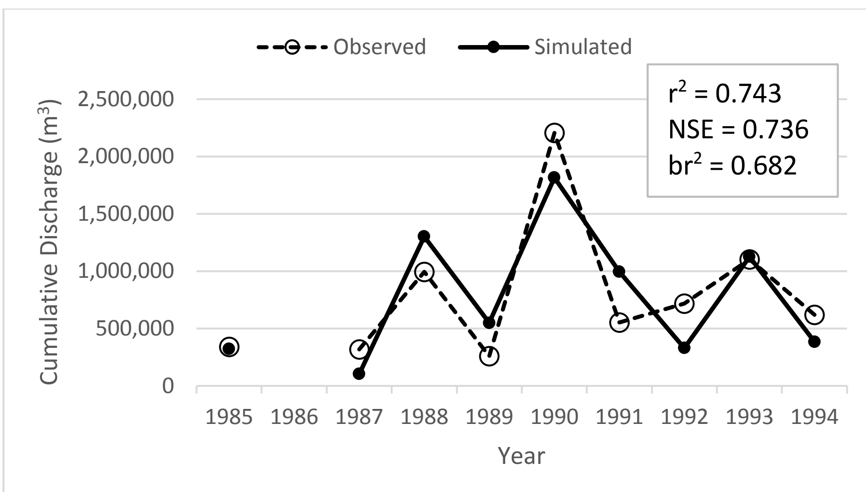

Figure 3-2. Simulated and measured yearly cumulative discharge for June 30th (1985-1994).

The physical and empirical hydrologic models performed well in simulating discharge at the study site. Interestingly, the SCS-CN performed more accurately than the MESH physical model. This provides evidence towards the notion that empirical models can perform the same or better than physical models (King et al., 1999). However, the SCS-CN method did not capture spring runoff well. This led to the inclusion of the RO method which did not perform as accurately as the SCS-CN method ($r^2 = 0.533$). When the performance of the RO and SCS-CN method are combined and compared to the MESH model, the two models performed well and had similar performance evaluations. For this reason, both hydrologic models were used within the modeling system. The resulting outputs could then be compared, providing further substantiation to the analysis.

3.2 Sensitivity Analysis Results

Reservoir and irrigation cost adjustments (5% increase and decrease, 10% increase and decrease) resulted in similar increases and decreases to net revenue. A net revenue of -$160.00/hectare became -$176.00/hectare when reservoir and irrigation costs were increased by 10%. Slight variation to net revenue percent increases and decreases was experienced (average variation of 1%) due to operating costs, also being subtracted from gross revenue, remaining constant. Sensitivity analyses of crop price did have an effect on yearly revenue. As crop price increased, the impact on gross crop revenue increased (Table 3-1). The nonlinearity of the impact of crop price variation was due to the variability in the precipitation time series and the nonlinear water sufficiency curves. The irrigation algorithm used for irrigation application also resulted in a slightly higher standard deviation when crops were irrigated versus non-irrigated crops. As crop yield fell to 80% of actual yield, irrigation was triggered. In some instances this would have been caused by an excess of water, rather than a lack of available water. In these cases, irrigation application would reduce yield.

Table 3-1. Sensitivity analysis illustrating average net revenue change (%) when crop prices on non-irrigated and irrigated crops were adjusted. Base crop prices: 1) alfalfa - \$132.28/tonne, 2) barley - \$173.23/tonne, 3) canola - \$418.87/tonne, 4) spring wheat - \$238.83/tonne.

Scenario	Net Revenue Average Change on Irrigated Crops (%)	Standard Deviation of Net Revenue Average Change on Irrigated Crops	Net Revenue Average Change on Non-Irrigated Crops (%)	Standard Deviation of Net Revenue Average Change on Non-Irrigated Crops
10% Crop Price Increase	+11.8	4.51	+11.7	4.19
10% Crop Price Decrease	-8.56	3.69	-8.66	3.42
25% Crop Price Increase	+27.1	5.13	+26.9	4.76
25% Crop Price Decrease	-23.8	3.07	-23.9	2.85
50% Crop Price Increase	+52.3	6.16	+52.1	5.72
50% Crop Price Decrease	-49.2	2.05	-49.3	1.90

The sensitivity analysis on initial reservoir water volume had very limited impact on gross revenue. All scenarios provided gross revenue changes below 0.1%. Variance to maximum daily irrigation water volume had a small effect in most scenario years, except in year 2013 (Table 3-2). The impact in 2013 was more substantial, with higher volumes of water providing up to 38% greater revenue. The year 2013 experienced the second lowest precipitation during the growing season (200 mm). There was also no initial water available in the reservoir. The variability in precipitation in 2013 provided conditions requiring significantly more irrigation than the other eleven simulated years.

Table 3-2. Sensitivity analysis illustrating average net revenue change when maximum daily irrigation water volume on irrigated crops were varied (base maximum daily irrigation water volume is 15,000 m^3).

Maximum Daily Irrigation Water Volume Withdrawal	Net Revenue Average Change (%)	Net Revenue Standard Deviation
75000 m^3	+4.64	10.9
65000 m^3	+4.64	10.9
55000 m^3	+4.56	10.8
45000 m^3	+4.49	10.8
35000 m^3	+3.86	9.08
25000 m^3	+3.03	6.60
5000 m^3	+0.592	3.13

The last sensitivity analysis was performed on the gap between actual and optimum yield. Net crop revenue fluctuated on average less than 2% (4.3 standard deviation) in all four scenarios. This indicated that within the model, crop yield was not sensitive to the timing of irrigation application when soil water levels were at levels that provided 60% or higher optimal yield as the crops were already receiving adequate water for optimal growth.

3.3 Objective 1: Results

Objective 1: Evaluate the capacity of retention ponds used for irrigation purposes to provide a net economic advantage for farmers not currently utilizing an on-farm water retention system for irrigation application.

The modelling system was run for the 2002 to 2014 time period using hydrologic inputs from the empirical and physically based models which resulted in two sets of simulations. Annual net revenue was calculated for the 2002 to 2014 time period with and without irrigation for each simulation series. The irrigation scenarios included the significant costs of irrigation and reservoir infrastructure. Utilizing water abstractions from the Pelly's Lake retention system, crops under irrigation experienced a decrease in net revenue when compared to values without irrigation and associated retention system and irrigation infrastructure. Figure 3-3 reports the yearly net revenue with and without irrigation as well as yearly precipitation amounts during the growing season. Reservoir levels for each growing season are also provided. Table 3-3 provides the difference in net revenue experienced when irrigation and associated infrastructure costs were taken into account. A negative value in Table 3-3 indicates a reduction in net revenue when infrastructure was installed and irrigation was applied while a positive value indicates an increase in revenue. The yearly average cost of the retention pond and irrigation infrastructure was $160.00/hectare. Any value above -$160.00 indicated that the increased crop yield from irrigation water offset the yearly cost of the retention pond and irrigation infrastructure. A value above zero would indicate all retention pond and irrigation infrastructure costs were being offset by increased crop yield under irrigation application.

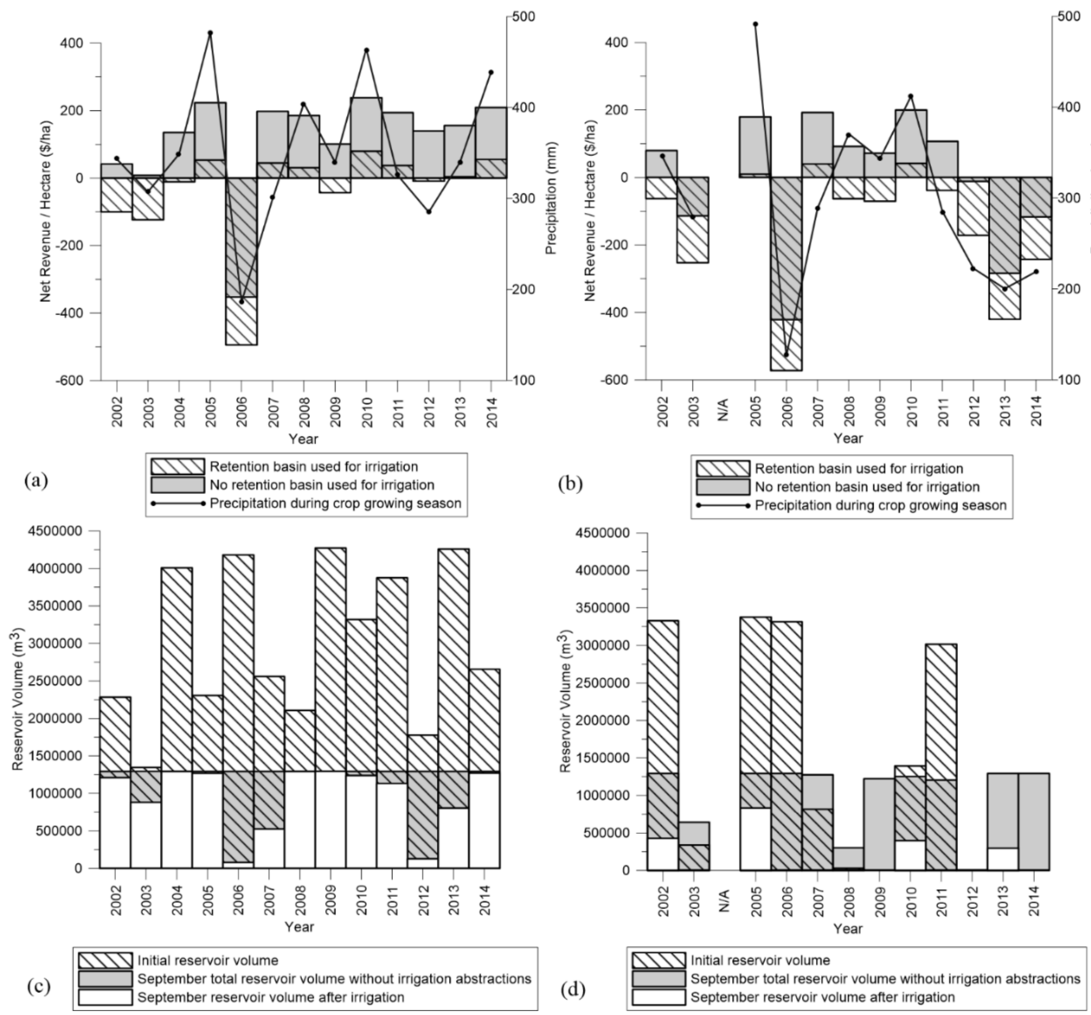

Figure 3-3. Yearly net crop revenue with and without irrigation application and yearly water availability for (a) RO/SCS-CN hydrologic input and (b) MESH hydrologic input. Reservoir volumes using hydrologic input from (c) RO/SCS-CN and (d) MESH. Irrigation infrastructure and associated costs were not included when the retention basin was not used for irrigation.

Table 3-3. Difference in average net crop revenue with irrigation relative to average net crop revenue without irrigation and the associated operating and infrastructure costs ($/hectare).

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Mean
MESH	-143	-139	n/a	-160	-151	-153	-155	-142	-158	-145	-160	-136	-126	-147
RO/ SCS-CN	-142	-132	-146	-160	-142	-153	-154	-144	-158	-157	-149	-152	-154	-150

Note: Difference = Net revenue with retention pond used for irrigation – Net revenue without retention pond installation and associated irrigation

Available precipitation strongly influenced the benefits of irrigation for the study period. Years that experienced precipitation levels above 400 mm within the growing season resulted in irrigation having little or no impact on crop yields as crop water requirements were being met or exceeded. The year 2005 experienced 490 mm of precipitation during the growing season (Figure 3-3) resulting in over $200 million in claims for crop flooding across Manitoba (MASC, 2015). Figure 3-4 provides a breakdown of crop insurance claims within the Victoria and Lorne census areas, which Pelly's Lake is situated within. In 2005, irrigation water from the Pelly's Lake reservoir system provided no production benefits with average net crop revenue being equal to the yearly cost of the reservoir and associated infrastructure ($160.00/hectare) (Table 3-3). Precipitation exceeded crop water requirements, therefore irrigation was not required. The year 2010 in both simulations, along with 2008 and 2014 in the RO/SCS-CN simulations, also experienced precipitation levels above 400 mm and experienced minimal impact to net crop revenues, $2.00/hectare and $6.00/hectare respectively.

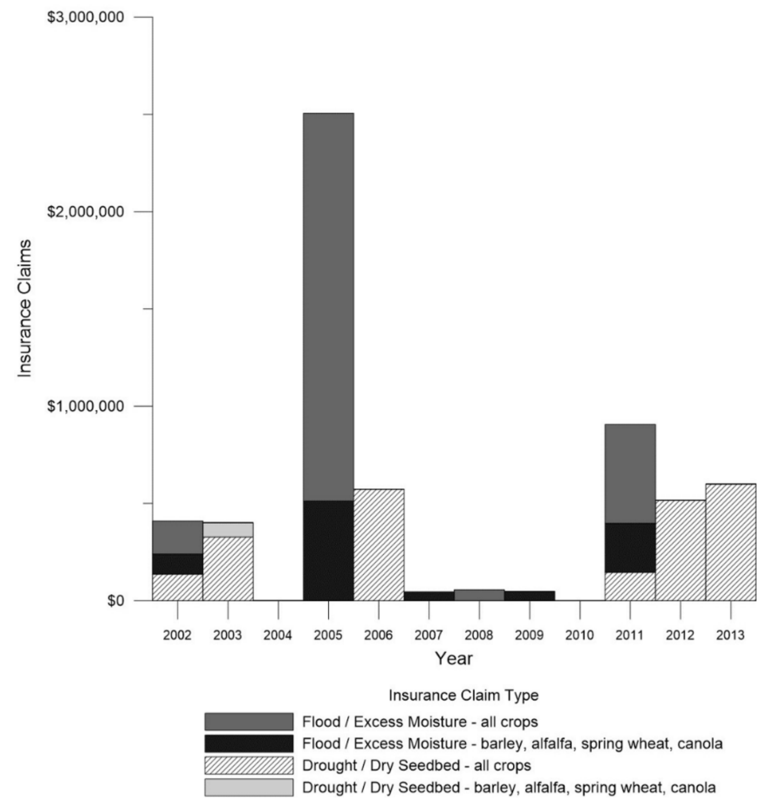

Figure 3-4. Agricultural claims for the Victoria and Lorne census areas which lie within the study watershed (MASC, 2015).

Crop yields increased with irrigation when precipitation levels were below 400 mm. Years 2002-2003, 2004 (RO/SCS-CN simulation), 2006-2007, 2008 (RO/SCS-CN simulation), 2009, 2011-2013, and 2014 (MESH simulation) experienced precipitation levels below 400 mm. Lower precipitation levels allowed irrigation to increase crop yields slightly, and thus increase gross crop revenue. The result was a gain in net crop revenue ranging from $3.00/hectare in 2011 (RO/SCS-CN simulation) to $34.00/hectare in 2014 (MESH simulation). The only year that did not see crop yield gains under irrigation when precipitation was below 400 mm for the growing season was 2012 (MESH simulation). Precipitation during the 2012 growing season was 222 mm yet irrigation had no impact on crop yield. The 2012 crop year experienced claims within the watershed's census areas for drought and dry seedbed and the initial reservoir volume in 2012 was minimal at 2,160 m^3 (Figure 3-3). The low initial reservoir volume indicated there was little spring runoff and thus initial soil moisture would be low. The 2012 MESH simulation year also experienced the lowest total reservoir volume for the growing season of 6,000 m^3 (1,030,000 m^3 average volume, 433,000 m^3 standard deviation). As a result, in that year irrigation water was not applied to the crops because of the low reservoir volumes. The RO/SCS-CN simulation experienced 285 mm of precipitation during the growing season. However, unlike in the MESH simulation, the initial reservoir volume was at full capacity allowing for irrigation application to increase net crop revenue by $11.00/hectare.

The year 2006 was used to simulate the economic benefits of partially or completely converting crop land to the high value potato crop, the most commonly irrigated crop in Manitoba, and applying irrigation across all crops or isolated to potato crops. Figure 3-5 indicates gross revenue did increase as the percentage of crop land allocated to potato increased. Isolating irrigation just to potato instead of distributing across all four crops had no observable impact. The potato crops water requirement was being sufficiently when irrigation water was distributed across all four crops during the 2006 simulation year. The high production costs associated with potato crops ($5,807/hectare) resulted in net revenue decreasing as the percentage of crop allocated to potato increased (Figure 3-6).

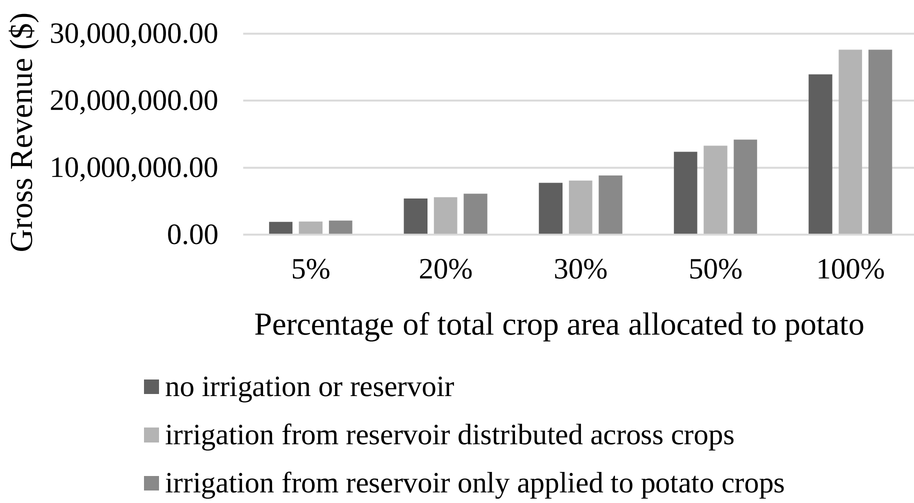

Figure 3-5. Study area gross revenue for the 2006 simulation year under various irrigation application scenarios using four crops (alfalfa, canola, wheat, potato) and adjusting the percentage of crop area allocated to potato.

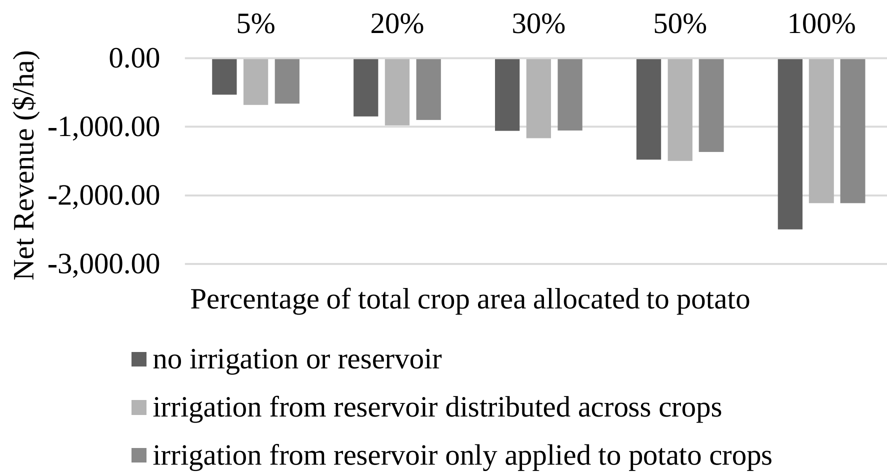

Figure 3-6. Net revenue for the 2006 simulation year under various irrigation application scenarios using four crops (alfalfa, canola, wheat, potato) and adjusting the percentage of crop area allocated to potato.

The average impact of irrigation application over the period of study in the MESH and RO/SCS-CN simulations was an increase in annual crop revenue of $12.80/hectare and $9.96/hectare respectively. However, due to the cost of irrigation and reservoir installation this on average left a net cost of $147.00/hectare (MESH simulations) to $150.00/hectare (RO/SCS-CN simulations) each year in order to cover the infrastructure and operation costs. Despite the yearly variance in reservoir volumes and net crop revenues between the MESH and RO/SCS-CN simulations, the average net crop revenue results for the simulation period were very similar. Converting cropland to the high value potato crop did not provide a positive net revenue when irrigation was applied. Irrigation and reservoir installation at Pelly's Lake remain too costly to enable positive net crop revenue throughout the simulation period, even when low value crops are converted to high value potato crops.

3.4 Objective 2: Results

Objective 2: Determine the economic advantage of using retention basins for biomass production and nutrient retention.

The retention basin at Pelly's Lake, MB provides economic and environmental benefits when biomass production capacity and nutrient retention are considered. Using the retention basin for cattail production and harvest directly benefits the farmer and also provides additional benefits to the province of Manitoba through carbon sequestration and nutrient removal from surface water. Harvesting cattails for biomass from the retention basin at Pelly's Lake, MB can provide an actual realized value of $642.70/hectare of harvestable cattail/year (Table 3-4). This value considered the current revenue gains available for cattail biomass and carbon offset credits.

Table 3-4. Actual realized values of harvesting cattails for biomass at Pelly's Lake, MB.

Variable	Units	Monetary Value ($/unit)	Annual Impact	Monetized Impact ($/yr)	Value ($/ha)
Cattails produced	Tonnes of cattails (total biomass)	16.59	1,815	30,110	248.90
Carbon credits	Tonnes of carbon dioxide equivalent	25.00	1,906	47,650	393.80
Total				77,760	642.70

Monetizing the ecosystem goods and services of carbon offset credits using a global social carbon credit value increases the value of biomass production at Pelly's Lake. The higher carbon credit value combined with the monetized value of phosphorus and nitrogen removed from the ecosystem during cattail harvest from the retention basin at Pelly's Lake, MB provides a monetized benefit of $8,014/hectare of harvestable cattail/year (Table 3-5).

Table 3-5. Monetized ecosystem goods and services benefits of harvesting cattails for biomass at Pelly's Lake, MB.

Variable	Units	Monetary Value ($/unit)	Annual Impact	Monetized Impact ($/yr)	Value ($/ha)
Carbon credits	Tonnes of carbon dioxide equivalent	63.50	1,906	121,000	1,000
Phosphorus removed	Kg of phosphorus	60.00	2,420	145,200	1,200
Nitrogen removed	Kg of nitrogen	36.34	19,360	703,500	5,814
Total				969,700	8,014

In addition to the economic and environmental benefits cattail harvest at Pelly's Lake, MB can provide, the retention basin itself provides nutrient removal, carbon sequestration, and avoided flooding costs. Monetizing these ecosystem goods and services benefits of retention basins, there is potential to gain $18,470.00/hectare of retention basin/year from its installation at Pelly's Lake (Table 3-6).

Table 3-6. Monetized additional ecosystem goods and services benefits of the retention basin at Pelly's Lake, MB.

Variable	Units	Monetary Value ($/unit)	Impact	Monetized Impact ($/yr)	Value ($/ha)
Carbon credits	Tonnes of Carbon	63.50	393.3	24,970	206.30
Phosphorus removed	Kg of phosphorus	60.00	9,680	580,800	4,800
Nitrogen removed	Kg of nitrogen	36.34	42,350	1,539,000	12,720
Avoided flooding costs	Hectares	741.30	121	89,700	741.30
Total				2,234,470	18,470

The valuation of avoided flooding costs based on the average global wetland flood control value found in Table 3-6 was higher than avoided flooding infrastructure damage cost estimates from a report in the rural municipality of Stanley, MB (Brander et al., 2013; Schuyt and Brander, 2004; Stanley Soil Management Association, 2000). It is important to note that while flooding did occur in the municipality during the reporting period, insurance claims for excess water and flooding in the area were not extensive as flooding only affected a small portion of the area (Manitoba Agricultural Services Corporation, 2015). Subsequently, there was potential for the municipality to experience more infrastructure damages and costs with widespread flooding events. Using the Stanley Soil Management Association analysis and adjusting for 2016 prices, a small dam network would provide savings of $0.55/ha in infrastructure damages (Table 3-7).

Table 3-7. Road and culvert damages due to flooding in the rural municipality of Stanley for 1995-1998 and adjusted prices for 2016.

Year	Culvert/Road Damages ($)	Adjusted for 2016 dollars ($)
1995	29,321	43,006.38
1996	28,877	41,732.98
1997	53,289	75,561.68
1998	12,960	18,195.21
Total	124,447	178,496.25
Average Annual	31,000 ($1.52/ha)	44,624 ($2.19/ha)
Reduction of damages with small dam network installation	7,750 ($0.38/ha)	11,156 ($0.55/ha)

In the study watershed, this estimate provided an annual average foregone costs of $15,235.00. Taking into account the two differing valuations of avoided flooding damages, the range in annual average foregone flooding costs in the study watershed due to the Pelly's Lake, MB retention basin installation was $15,235.00/year to $89,700.00/year. This provides a range in the ecosystem goods and service benefits of the retention system at Pelly's Lake of $2,160,000 - $2,234,470/year ($17,850 – $18,470/hectare of retention system/year). The yearly actual realized value of biomass harvest at Pelly's Lake provides an additional $77,760/year ($642.70/area of harvestable cattail/year), while the monetized ecosystem goods and services of cattail harvest provides $969,700/year ($8,014/area of harvestable cattail/year).

3.5 Objective 3: Results

Objective 3: Explore the economic advantages associated with retention ponds under future climatic conditions.

Annual net revenue was estimated from model simulations with and without irrigation for the middle of the century, 2050 to 2059, and the end of the century, 2090-2099. The simulation results indicate irrigated crops utilizing water abstractions from the reservoir experienced a decrease in net revenue when compared to net revenue without irrigation and associated infrastructure for both study simulation periods. Table 3-8 reports the difference in revenue experienced when irrigation and associated infrastructure costs were taken into account for the two study simulation periods. The four climate models were averaged for each RCP scenario to provide a multi-model average. The averaged results for the RCP4.5 scenario using incremental percentage increases to the 2005-2014 MESH climate data for the 2050s and 2090s are also provided in Table 3-8. A negative value in Table 3-8 indicates a reduction in net revenue when infrastructure was installed and irrigation was applied while a positive value indicates an increase in net revenue. The estimated yearly cost of the retention pond and irrigation infrastructure was $160.00/hectare. Any value above -$160.00 indicated that the increased crop yield from irrigation water offset the yearly cost of the retention pond and irrigation infrastructure. A value above zero would indicate all retention pond and irrigation infrastructure costs are being offset by increased crop yield under irrigation application. Unlike in the 2002-2014 simulation period, all years within the study time periods experienced increased crop yield from irrigation water. Yearly net revenue with and without irrigation and yearly precipitation amounts for the MESH and climate model simulations are provided in Appendix A.

Table 3-8. Average difference in net crop revenue without irrigation and net crop revenue with irrigation and associated operating and infrastructure costs ($/hectare) for each climate model, the multi-model average, and the MESH average. Standard deviation shown in parantheses.

Scenario	Climate Models				Multi-Model Average	MESH Average
	MPI-ESM-LR	HadGEM2-ES	GFDL-ESM2G	CanESM2		
2050-2059						
RCP2.6	-151 (10.6)	-146 (11.0)	-143 (11.8)	-145 (11.0)	-146 (11.5)	n/a
RCP4.5	-143 (12.3)	-145 (11.6)	-150 (6.48)	-144 (11.6)	-145 (11.1)	-149 (13.4)
RCP8.5	-141 (13.2)	-136 (12.2)	-153 (9.56)	-142 (7.73)	-143 (12.5)	n/a
2090-2099						
RCP2.6	-148 (9.57)	-145 (10.6)	-140 (12.6)	-143 (9.02)	-144 (10.9)	n/a
RCP4.5	-143 (12.6)	-143 (10.5)	-151 (11.5)	-141 (9.82)	-145 (11.8)	-149 (14.0)
RCP8.5	-151 (10.6)	-146 (9.48)	-156 (7.00)	-140 (9.84)	-148 (10.9)	n/a
Note: Difference = Net revenue with retention pond used for irrigation – Net revenue without retention pond installation and associated irrigation						

The multi-model average impact of irrigation on gross annual crop revenue was higher for the 2050s and 2090s, with the exception of the 2090s under RCP8.5, than during the 2002-2014 simulation period (Table 3-9). The MESH average increase in gross crop revenue under irrigation fell between the MESH and RO/SCS-CN simulation values for 2002-2014. Average increases to annual crop revenue for the 2002-2014 simulation period were $12.80/hectare for MESH simulations and $9.96/hectare for the RO/SCS-CN simulations.

Table 3-9. Increase in gross crop revenue under irrigation ($/hectare) for each climate model, averaged over the four climate models, and the MESH average.

Scenario	Climate Models				Multi-Model Average	MESH Average
	MPI-ESM-LR	HadGEM2-ES	GFDL-ESM2G	CanESM2		
2050-2059						
RCP2.6	8.99	14.6	16.8	15.0	13.8	n/a
RCP4.5	17.3	15.5	10.1	16.1	14.8	11.66
RCP8.5	18.5	24.0	7.19	18.0	16.9	n/a
2090-2099						
RCP2.6	12.0	15.6	19.7	17.6	16.2	n/a
RCP4.5	17.3	17.5	9.00	18.9	15.7	11.62
RCP8.5	9.00	14.4	4.68	19.9	12.0	n/a

The multi-model average impact of irrigation on gross crop revenue increased as the RCP radiative forcing increased for the 2050-2059 simulation period. During the same simulation period, average irrigation volume used during the growing season also increased with RCP radiative forcing (Table 3-10). The MESH average impact of irrigation on gross crop revenue for RCP4.5 was less than the RCP4.5 multi-model average. In MESH, more irrigation was applied than in the climate model simulations. The 2090-2099 simulation period experienced the opposite, with the multi-model average impact of irrigation on gross crop revenue decreasing as RCP radiative forcing increases. As with the 2050s simulation period, MESH average gross crop revenue from irrigation application was lower than the multi-model averages and more irrigation water was applied to crops. The multi-model average application of irrigation water decreased from the 2002-2014 average irrigation application of 867,975 m^3 (MESH simulations) and 338,226 m^3 (RO/SCS-CN simulations). Irrigation volume averages for the 2050s and 2090s are provided in Table 3-10.

Table 3-10. Average irrigation volume used during the growing season (m^3/year) for each climate model, the multi climate model average, and the MESH average.

Scenario	Climate Models				Multi-Model Average	MESH Average
	MPI-ESM-LR	HadGEM2-ES	GFDL-ESM2G	CanESM2		
2050-2059						
RCP2.6	491,780	905,424	712,433	862,398	743,009	n/a
RCP4.5	896,445	884,926	629,373	849,216	814,990	929,313
RCP8.5	1,023981	1,075,936	406,686	956,449	865,763	n/a
2090-2099						
RCP2.6	503,760	780,595	909,865	971,170	791,348	n/a
RCP4.5	777,577	927,630	367,362	843,645	729,054	967,533
RCP8.5	752,380	1,068,700	126,930	842,525	697,634	n/a

These results can be explained by the precipitation increases experienced in the 2050s and 2090s. Increased precipitation reduced the need for irrigation application to meet optimal crop growth. Average summer precipitation for the 2050s and 2090s, under RCP4.5, increased from 2002-2014 average precipitation levels by 1.3% and 2.5% respectively. Table 3-11 provides the precipitation ranges in all three study periods and under all three RCPs. Average winter precipitation increased more dramatically over 2002-2014 average precipitation levels with an 8.8% increase by the 2050s and 16.6% increase by the 2090s. Increases in winter precipitation ensured the reservoir filled to capacity at the beginning of the growing season at Pelly's Lake every year during the 2050s and 2090s simulation periods when using PCIC climate data. Refer to Appendix A for climate model reservoir volumes during the 2050s and 2090s simulation periods. The increased precipitation, in combination with water available for irrigation provided the increases, in comparison to 2002-2014 results, to 2050s and 2090s gross crop revenue under irrigation.

The MESH simulations, in which 2005-2014 climate data was incrementally increased, resulted in two years in the 2050s having minimal initial reservoir volume. When no irrigation abstractions were made, one year in the MESH simulations experienced an empty reservoir at the end of the growing season. The 2090s MESH simulations experienced four years with little or no initial reservoir volume. However, during the course of the growing seasons the reservoir filled, allowing for irrigation withdrawals, with the exception of 2097 which did not experience enough precipitation during the growing season to provide water for irrigation. Reservoir volumes for MESH simulations are reported for the 2050s and 2090s in Appendix A. Even though MESH simulations abstracted more water for irrigation than the multi-model simulations, revenue results remained less favourable. As the MESH simulations used climate data from 2005-2014, weather patterns in precipitation reflected that time period. The detailed explanation of the 2005-2014 MESH simulation results is provided in Section 3.3. The weather patterns produced by the four climate models acquired from PCIC appeared to provide more favourable conditions for optimizing crop growth under irrigation.

Table 3-11. Range in summer precipitation for all study simulation periods and models. Multi-model average summer precipitation ranges from PCIC data input into the RO/SCS-CN hydrologic model are recorded for the 2050s and 2090s.

Scenario	RO/SCS-CN precipitation inputs (mm)	MESH precipitation inputs (mm)
2002-2014		
n/a	186 - 482	126 - 491
2050-2059		
RCP2.6	232 - 541	n/a
RCP4.5	155 - 531	130 - 498
RCP8.5	224 - 536	n/a
2090-2099		
RCP2.6	122 - 532	n/a
RCP4.5	162 - 536	132 - 504
RCP8.5	218 - 639	n/a

The average impact of irrigation application for the 2050s simulation in the MESH simulations was an increase in annual crop revenue of $11.66/hectare. The multi-model average increase in annual crop revenue was $13.80 – $16.90/hectare, increasing with RCP radiative forcing. However, due to the cost of irrigation and reservoir installation, this on average left the farmer with a net cost of $143.00 - $149.00/hectare each year in order to cover the reservoir and irrigation infrastructure and operation costs. For the 2090s simulations, the average impact of irrigation application in the MESH simulations was an increase in annual crop revenue of $11.62/hectare. The multi-model average increase in annual crop revenue was $12.00/hectare, decreasing with RCP radiative forcing. This on average left the farmer with a net cost of $144.00 - $149.00/hectare each year in order to cover the reservoir and irrigation infrastructure and operation costs. Despite the yearly variance in reservoir volumes and net crop revenues between the MESH and RO/SCS-CN simulations, the average net crop revenue results for the simulation period were within the same range. Differences between RCP scenarios did not have a significant enough impact on gross crop revenue to increase or decrease the economic benefits of using retention ponds for irrigation. Based on these simulation results, using the reservoir installation at Pelly's Lake for irrigation is not economically viable to experience positive net crop revenue in the middle or end of the century.

CHAPTER 4

DISCUSSION AND CONCLUSIONS

This chapter will begin with a discussion of the findings of this research and the feasibility of multi-purpose surface water retention systems as an economically viable, strategic water management strategy in Manitoba. The discussion will conclude with a section outlining potential policy recommendations. A conclusions section will follow the discussion. The limitations of this study will be outlined. Potential future work that can occur as a result of this study will follow. The chapter will finish with a discussion on how this research contributes to sustainability and is scholarly and societally relevant.

4.1 Discussion

The economic benefits of adopting multi-purpose on-farm surface water retention basins as a strategic water management strategy were investigated using a dynamic modelling system to address three main objectives. The first objective was to determine retention ponds capacity when used for irrigation purposes to provide a net economic advantage for farmers currently without an on-farm retention system or irrigation infrastructure. Retention ponds used for irrigation on the study watershed's four main crops from 2002-2015 provided an average annual increase in gross crop revenue of $11.38/hectare. However, due to the high cost associated with the installation and maintenance of the retention pond and irrigation equipment, the net cost to the participating farmer was an average of $148.50/hectare each year. Replacing the existing low value crops within the study area with high value potato crops also resulted in a negative net revenue. Objective one results indicated that under current climate conditions, installation of retention basins for irrigation purposes remained not an economically viable investment for the farmer.

In the analysis it was assumed that the farmer would be responsible for all costs associated with reservoir and irrigation infrastructure and maintenance. However, there is currently funding available within Manitoba to subsidize the cost of installing reservoirs due to their multiple downstream benefits including wildlife habitat, carbon sequestration, phosphorus removal and flood mitigation. The Growing Assurance Ecological Goods and Services Program, part of the Federal-Provincial initiative Growing Forward 2, is providing funding from 2013 to 2018 (Government of Manitoba, 2015b). There is also funding available through non-profit organizations such as the Manitoba Conservation District Association. For the Pelly's Lake reservoir, a total of $107,000 in project management costs were covered by the LSRCD and its partners (LSRCD, 2015b). Applied to the overall cost of the reservoir, the in-kind contributions from LSRCD reduced the yearly reservoir costs to farmers at Pelly's Lake by $1.62/ha/year. However, irrigation installation is not currently being subsidized in Manitoba. The average annual increase to crop revenue of $11.38/hectare does not merit irrigation infrastructure installation at an annual cost of $152.00/irrigated hectare. As average insurance costs for the four crops analyzed within the study site were $42.57/hectare as of 2015, it makes more sense for the farmer to invest in insurance rather than irrigation (Government of Manitoba, 2015a).

It is also important to note that the results from this study appear to be localized and represent the specific crop growth and irrigation characteristics of the target watershed. At the provincial level, 2002 and 2003 reported the third and second highest agricultural claims for drought ($19.5 million and $25 million, respectively) while 2006 experienced the highest level of drought insurance claims in the province ($27 million) (MASC, 2015). However, within the Victoria and Lorne census areas, which were the target of the present research, 2002 and 2003 received far more precipitation than in 2006 and had much lower insurance claims for drought (MASC, 2015). Drought insurance claims within the Victoria and Lorne census areas were instead higher in 2012 and 2013, which provincially saw low insurance claims ($18 million and $22.5 million lower than 2006 claims, respectively) (MASC, 2015). In 2010, Manitoba experienced $169 million in claims for flooding (the second highest between 2002 and 2014) while the Victoria and Lorne census areas did not have any claims for flooding that year (MASC, 2015).

Using the multi-purpose retention basin solely for irrigation does not make economic sense if the farmer is required to cover the retention basin installation and irrigation infrastructure costs. It is also important to consider property rights when designing and implementing multi-purpose retention systems. Each landowner will need to see the benefit of a retention system development on their land. The second objective explored the economic benefits of multi-purpose retention systems capacity for biomass production, carbon sequestration, nutrient retention, and avoided flood damages. Harvesting cattails from the retention site for biomass and associated carbon offset credits, actual realized values, covers the yearly amortized cost of the reservoir and irrigation. It can also provide an increase in net revenue of $482.70/hectare of retention basin/year. In the case of Pelly's Lake, one landowner owns the land on which the retention system is located. They would be benefitting from the additional revenue from cattail harvest, while downstream landowners would be directly benefitting from avoided flood damages. Monetizing the additional ecosystem goods and services benefits of cattail harvest, provides $8,014.00/hectare of retention basin/year. The province of Manitoba would be realizing these benefits as the province has yet to develop a market providing farmers with nitrogen and phosphorus capture credits. However, the actual realized values of cattail harvest allows the farmer to invest in retention basin and irrigation infrastructure enabling crop production stabilization and risk reduction in the face of predicted changes to precipitation and temperature in the future (Hassanzadeh et al., 2014; Pittman et al., 2011).

The removal of phosphorus, nitrogen, carbon, and avoided flooding damages of the retention basin itself provided an estimated additional $2,160,000/hectare of retention basin/year using a conservative valuation of avoided flooding damages. A conservative estimate was also used for wetland phosphorus absorption of 80 kg/hectare/year. Olewiler (2004) estimated wetlands can remove anywhere from 80 to 770 kg/hectare/year of phosphorus. Using a value of $60.00/kg for phosphorus removed, a higher wetland phosphorus absorption rate would greatly increase the value of the multi-purpose retention system at Pelly's Lake, MB. There was also substantial variance in wetland nitrogen removal amounts and values. Nitrogen removal amounts ranged from 350 to 32,000 kg/hectare/year, while removal rates ranged from $7.45/kg to $140.10/kg (Collins and Gillies, 2014; Olewiler, 2004; S. Wilson, 2008). For this research, the low end nitrogen removal rate and a moderate value estimate of $36.34/kg for nitrogen removal from a constructed wetland was used. As with phosphorus, increasing these estimated rates would increase the value of the retention system at Pelly's Lake, MB.

Using multi-purpose retention basins for avoided flood damages, nutrient retention, and biomass production is not only economically beneficial to the farmer and government, but also to the environment. The province of Manitoba is committed to reducing downstream nutrient loading and have expressed interest in retention basins as a nutrient abatement option (Bourne et al., 2002; Government of Manitoba, 2014a; Grosshans et al., 2014; Lake Winnipeg Stewardship Board, 2006). Manitoba's Surface Water Management Strategy (2014a) states that water storage and associated release strategies should optimize production and harvest of biomass resources to remove phosphorus from the aquatic environment. Removing these nutrients from the landscape via harvest reduces downstream nutrient loading. Additionally, the removal of phosphorus during cattail harvest increases the wetlands ability to store more phosphorus, benefiting downstream loading. This is essential for combating algal blooms and increasing water quality in aquatic environments such as Lake Winnipeg, Manitoba (Grosshans et al., 2014).

As the South Tobacco Creek Watershed has illustrated, a series of retention systems on the Manitoba landscape has the potential to reduce downstream loading of phosphorus and nitrogen. Over a nine year period from 1999-2007, the retention system network decreased downstream nutrient loading above the Manitoba governments targets of 10% and 13% for phosphorus and nitrogen, respectively (Tiessen et al., 2011). As the average phosphorus and nitrogen concentrations in the watershed were still in excess of recommended levels in the Canadian Prairies, Tiessen et al. (2011) suggested using the reservoirs for local benefits, such as irrigation, would reduce downstream nutrient loading further. With the addition of cattail harvest, downstream loading of phosphorus and nitrogen would be further reduced.

As part of the retention system network in the South Tobacco Creek Watershed, Manitoba, a multi-purpose dam reduced peak flow caused by spring snowmelt by an average of 72% per year, with a range of 38% to 100% peak flow reduction/year. Summer rainfall generated peak flow was reduced an average of 48% per year by the same multi-purpose dam. The multi-purpose retention system at Pelly's Lake has only been operational for two years. However, in 2016, Pelly's Lake was already required to retain runoff from intense storm events in southwestern Manitoba. The reservoir at Pelly's Lake was full all summer and into the fall. As you can see in Figure 4-1, spring melt runoff can often overwhelm the storage capacity of the downstream reservoir at Pelly's Lake. There is discussion about constructing a second upstream reservoir which would increase storage capacity by 1,600,000 m^3. This would greatly improve the retention systems ability to retain the majority or full volume of spring melt runoff.

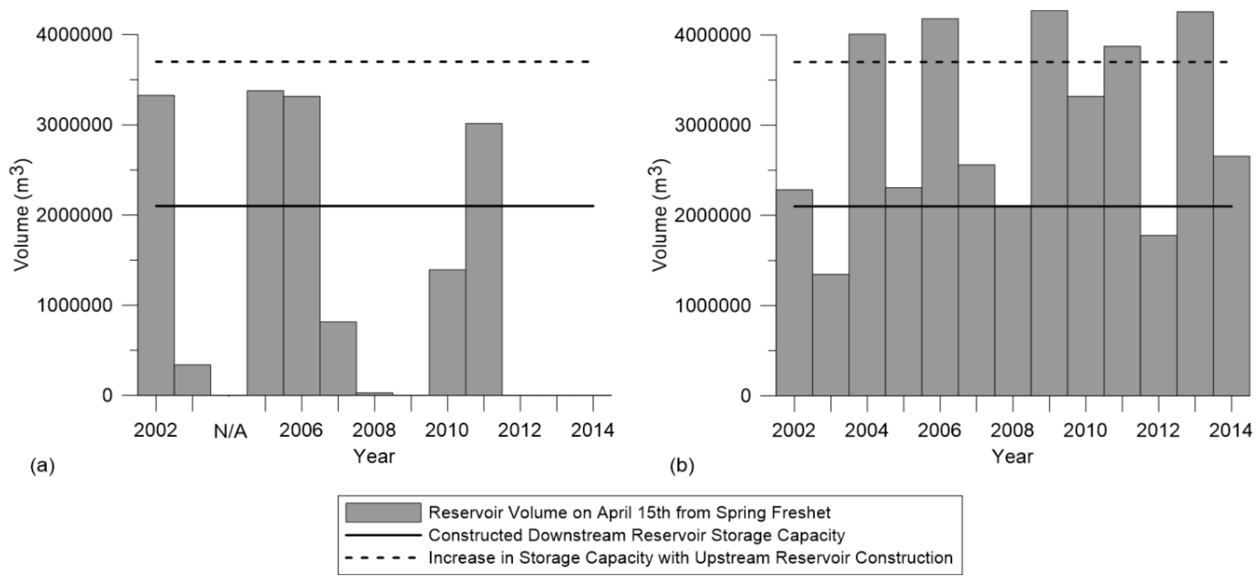

Figure 4-1. Reservoir capacities and initial reservoir volumes under (a) MESH and (b) RO/SCS-CN hydrologic inputs.

Not all benefits of retention basins were included in this analysis. Reductions to downstream flooding also reduces damage to livestock, machinery, infrastructure, and crop lands. Retention basins also provide wildlife habitat and recreational services. At Pelly's Lake, the retention site is being used in a public education capacity. These benefits were not monetized in the current study as it is very difficult to determine an accurate value. However, inclusion of these benefits in the economic assessment would further increase the value of multi-purpose retention systems on the Manitoba landscape.

The retention basin installation at Pelly's Lake, with a total cost of $551,288 could be paid off soon after installation when all the benefits of the retention pond are considered. Investing in multiple on-farm multi-purpose retention systems also has the potential to provide environmental and social benefits to the province of Manitoba. The reductions in phosphorus and nitrogen multi-purpose retention systems provide can aid in Manitoba's goal of reducing nitrogen and phosphorus concentrations by 50% to Lake Winnipeg (Government of Manitoba, 2014a). Rural municipalities and landowners benefit from the savings associated with avoided flooding damages while the province of Manitoba and its population benefit from the reduction to downstream nutrient loading and carbon storage providing climate regulation.

The last objective explored the economic advantages of multi-purpose retention pond installation and use for irrigation under future climatic conditions. The middle of the century, 2050-2059, and the end of the century, 2090-2099, were simulated under three radiative forcing scenarios and using two modeling techniques. Irrigated crops utilizing water abstractions from the reservoir experienced a decrease in net revenue when compared to net revenue without irrigation and the associated infrastructure for both simulation periods, both techniques, and under all radiative forcing scenarios. To cover the costs of the irrigation and reservoir infrastructure, the farmer would have to pay $143.00 to $149.00/hectare/year in the 2050s and $144.00 to $149.00/hectare/year in the 2090s.

Future climate scenarios did however provide an increase in gross crop revenue when irrigation was applied for each simulation year. This was not the case for the 2002-2014 simulation period. Average annual gross crop revenue increases under irrigation ranged from $11.66 to $16.90/hectare/year for the 2050s simulation period, with RCP8.5 providing the largest increase. For the 2090s, the range was $11.62 to $16.20/hectare/year with RCP2.6 providing the largest increase to average annual gross crop revenue under irrigation. Irrigation use decreased under the RO/SCS-CN simulations for both simulation periods and all RCPs when compared to the 2002-2014 irrigation use. However, an increase in irrigation use was experienced for the RCP4.5 MESH simulations. As the future MESH simulations were based on the 2005-2014 climate data, weather patterns differ from the RO/SCS-CN simulations, and subsequently irrigation application need differed.

The multi model ensemble future climate scenarios indicated precipitation increases will occur in the 2050s and 2090s under each RCP scenario. Precipitation increases were higher for winter than summer. Several studies have predicted a general trend of increasing precipitation over Canada (Bonsal et al., 2011; Nyirfa and Harron, 2001; Sauchyn et al., 2002; Venema et al., 2010) The higher projected increases to precipitation for winter months was also supported in the literature for future climate change over Canada (Bonsal et al., 2011; IPCC, 2007a; Venema et al., 2010; Warren and Lemmon, 2014). The increased winter precipitation resulted in the reservoir filling to capacity each year for the 2050s and 2090s under RO/SCS-CN simulations. The predicted changes to the precipitation regime will affect crop productivity and returns of annual crops. Future MESH simulations resulted in the reservoir only filling to capacity at the beginning of the growing season for five years in the 2050s and six years in the 2090s. However, under both the RO/SCS-CN and MESH simulations, when the reservoir did fill to capacity there was substantial flow produced from spring melt that exceeded the capacity of the reservoir

(Figures A-1 to A-10). This indicated that the middle and end of the century will require strategies to reduce flood damages from large spring runoff volumes. Constructing an upstream reservoir at Pelly's Lake, with 1,600,000 m^3 additional capacity could help capture these higher predicted spring runoff volumes. A network of several multi-purpose retention systems, similar to the installed network in the South Tobacco Creek Watershed may be required to deal with the future increases to spring runoff volumes. The predicted increases in spring runoff volumes also suggest retention basins flood mitigating benefits may increase in value while the value of their use for irrigation may decrease or remain stable in the future.

The twelve-year present day time period of this study highlighted the extreme variation in water availability to which Manitoba farmers are required to adapt. As witnessed in 2005 and 2006, precipitation amounts ranged from one extreme to the next ,(491 mm, 2005 - 127 mm, 2006) requiring farmers to be prepared for flood and drought conditions each year. The nutrient retention, flood damage reductions, carbon sequestration, and biomass production capacity of multi-purpose retention systems may provide the necessary economic and environmental benefits for their widespread adoption. Farmers, even without government subsidies, can afford retention system installation to support irrigation practices if they choose to harvest cattails for biomass. Due to the economic and environmental gains multi-purpose retention systems provide to the province, subsidies could also be provided to incentivize widespread adoption. The predicted changes in precipitation amounts and timing on the Canadian Prairies due to climate change suggest that retention systems may prove even more economically feasible under future climate scenarios (Bonsal et al., 2011; Mailhot et al., 2010; Pacific Climate Impacts Consortium, 2014; Venema et al., 2010).

The current strategy for quickly removing water from the Manitoba landscape via a series of ditches and drains, increases downstream flood peaks and decreases water quality. This method is only sustainable when there is adequate access to water and land use practices do not create nutrient pollution issues (Venema et al., 2010). This quick drainage is already proving problematic for downstream nutrient loading into Lake Winnipeg. Future predictions of increased spring runoff volumes indicate increased issues with this strategy due to increased downstream flood peaks and increased nutrient loading. As drought severity and duration are predicted to increase in the future, drainage will exacerbate drought conditions by depleting groundwater reserves normally drawn upon during times of drought (Bonsal et al., 2011;

Venema et al., 2010). Moving forward, investing in multi-purpose retention systems decreases flood peaks, increases water quality, while also providing water security during times of drought, as well as opportunities for biomass production and irrigation development.

4.1.1 Potential Policy Recommendations

The results of this research lend themselves to several recommendations for policy makers to consider:

1) The substantial ecosystem goods and service benefits of multi-purpose retention systems merit subsidization of the cost of reservoir construction and yearly maintenance. This would increase their adoption rate and could be implemented via Manitoba's Conservation District Program.

2) Irrigation infrastructure investment is too high for farmers in Manitoba. To promote adoption of irrigation practices to reduce risk under climate change, subsidization of the cost of irrigation infrastructure installation could be offered through provincial agricultural best management practice incentives.

3) A system could be developed to provide farmers with direct payments for carbon sequestration and nutrient removal benefits from on-farm multi-purpose retention systems through initiatives such as ALUS or via trading systems for carbon or nutrient credits.

4) To ensure maximum ecological benefits of multi-purpose retention systems, guidelines and criteria for their design should be developed. This would require a team consisting of engineers, conservation district managers, and specialists on wetland management.

5) Assessments should be undertaken to determine the appropriate location, size, and number of retention system each watershed requires to ensure widespread adoption is tailored to maximize economic and environmental benefits.

4.2 Conclusions

4.2.1 Limitations

This research was limited by gaps in research as well as data availability. Irrigation pricing information for the province of Manitoba was limited, as was access to continuous historical meteorological data sets for Pelly's Lake, MB. This could not be avoided and would be problematic regardless of study site location on the Prairies. A large knowledge gap exists regarding groundwater. On the Prairies, where groundwater is often the only water source available to alleviate drought conditions, there is limited data on groundwater allocations, withdrawals, or available volumes. It thus becomes difficult to determine the efficacy of water management strategies on the Prairies without knowing what water reserves are available for use (Bonsal et al., 2011). While this did not directly constrain this research, it did not allow for the water storage capacity of retention systems to be compared to existing water availability. Additionally, evapotranspiration processes on the Prairies remain poorly understood and access to climate data required to estimate evapotranspiration is very limited. The values used for evaporation were 1981-2010 mean monthly values at Brandon, MB. As we did not have the data required to estimate evapotranspiration within the modelling system, the future climate scenarios did not account for temperature increases impacting evapotranspiration levels (Bonsal et al., 2011). The current understanding of climate conditions remains uncertain, leading to uncertainties in global climate model simulations and future climate change projections. Uncertainty is also present in RCPs as future technological advancements, socio-economic and demographic conditions remain uncertain. RCPs were run within multiple GCMs and averaged to create a multi-model ensemble considered to be a more probable future climate scenario. The economic model developed for the study was also simplistic. It did not account for the dynamic decision making farmers may include in their cropping decisions, such as choosing different crop rotations based on variables such as environmental conditions, output prices, and input prices.

4.2.2 Future Work

The modeling system developed for this research could be easily adapted to additional reservoirs within the catchment area, enabling regionalization. The RO/SCS-CN method hydrologic performance was reasonable, confirming it as a feasible and simple method for regionalization. The MESH hydrologic performance was also reasonable, however the method would require more substantive time and resources than the RO/SCS-CN method. As the current study is localized, it is difficult to state how well retention systems would work throughout the Red River Valley landscape. Regionalization of the study would also allow for the calculation of flow reductions over a larger area due to the installation of multiple retention systems. Comparisons could then be drawn between the effectiveness of water retention systems vs. current drainage systems on the Red River Valley landscape. Finally, regionalization of the study would allow for further sensitivity analyses to reduce uncertainty in the models performance and resulting outputs.

The modeling system could also be easily expanded to include additional modules of interest to the researcher. Water samples are being collected for Pelly's Lake, upstream and downstream of the reservoir. Inclusion of a module on sediment and nutrient levels would allow for a more accurate economic assessment based on the amount of phosphorus and nitrogen loading Pelly's Lake is reducing.

4.2.3 Sustainability

This research informs water management and policy on adaptation strategies in the face of climate change. The results contribute to several areas of priority within the Lake Winnipeg Basin: a) management of peak flows, b) agricultural nutrient loading reduction, and c) developing drought resilience on farm (Venema et al., 2010). Alternative sources of energy, such as cattails, are explored for their environmental benefits as well as their economic feasibility. This study adds to the literature focused on identifying and valuing the natural capital retention basins can provide. This research also impacts decision making at the farm level. Supporting on-farm surface water retention systems requires placement on potentially arable land. Providing knowledge on the economic and environmental benefits of this practice enables farmers to make informed decisions regarding land use on their property.

4.2.4 Scholarly and Societal Relevance

This research is relevant to society, as it provides an economic assessment valuable in informing policy on water management strategies. The knowledge gained from this research will inform the decision making process involved in determining whether widespread adoption of surface water retention systems should be implemented in the province of Manitoba.

Provincial agricultural bodies are gaining knowledge on the current and potential future state of Prairie water supplies and the affordability of irrigation. The benefits gained by installing retention pond systems due to their multi-purpose use is provided as an option for dealing with the uncertainties associated with future climate change. The modeling system produced from this research is generic enough to be adaptable for answering varying questions (such as biomass development) on the Prairies. In addition to furthering the literature on water management strategies, the analysis of future climate change effects adds to the body of research dedicated to predicting the impacts climate change will bring.

The research is part of a broader project based out of the University of Manitoba entitled "Innovative surface water and nutrient management initiatives on farm" aiming to explore options for storing water that also reduce nutrient and water release downstream. Subsequently, results from this study are informing collaboration efforts with researchers from the University of Waterloo and University of Manitoba where researchers are researching runoff and nutrient exports from agricultural fields and forage flooding tolerances, respectively.

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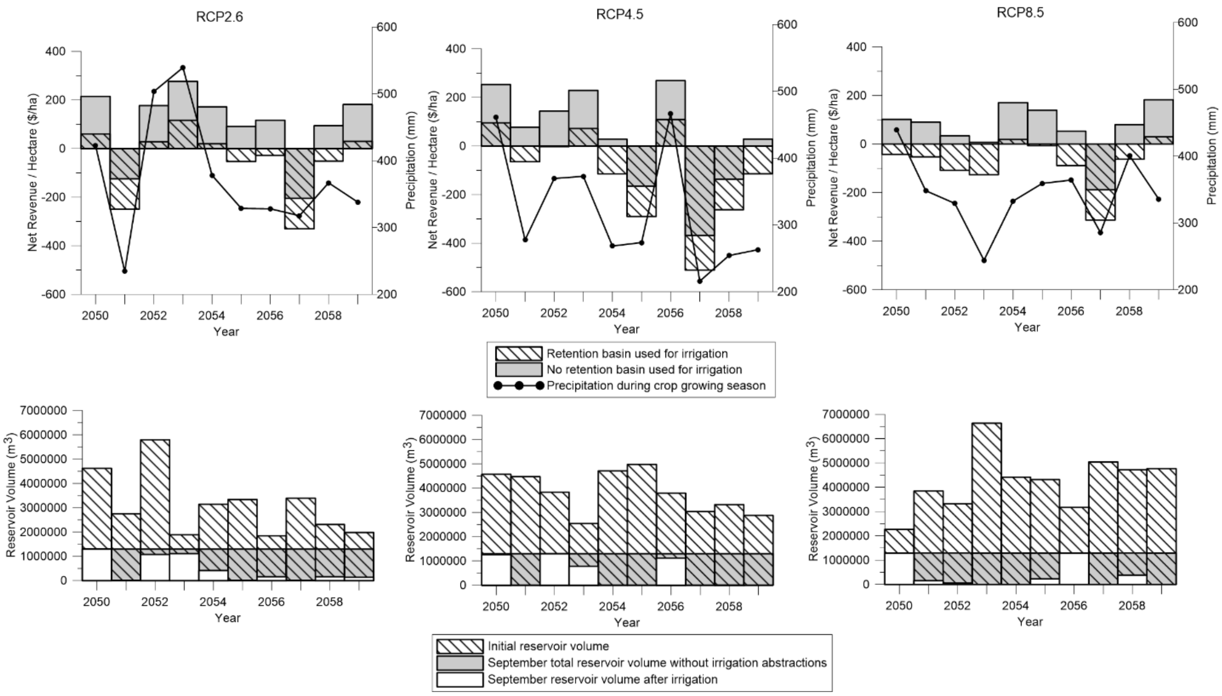

Figure A-1. Yearly 2050-2059 net crop revenue with and without irrigation application and yearly water availability for the CanESM2 climate model and each RCP. Reservoir levels from each RCP simulation are also provided.

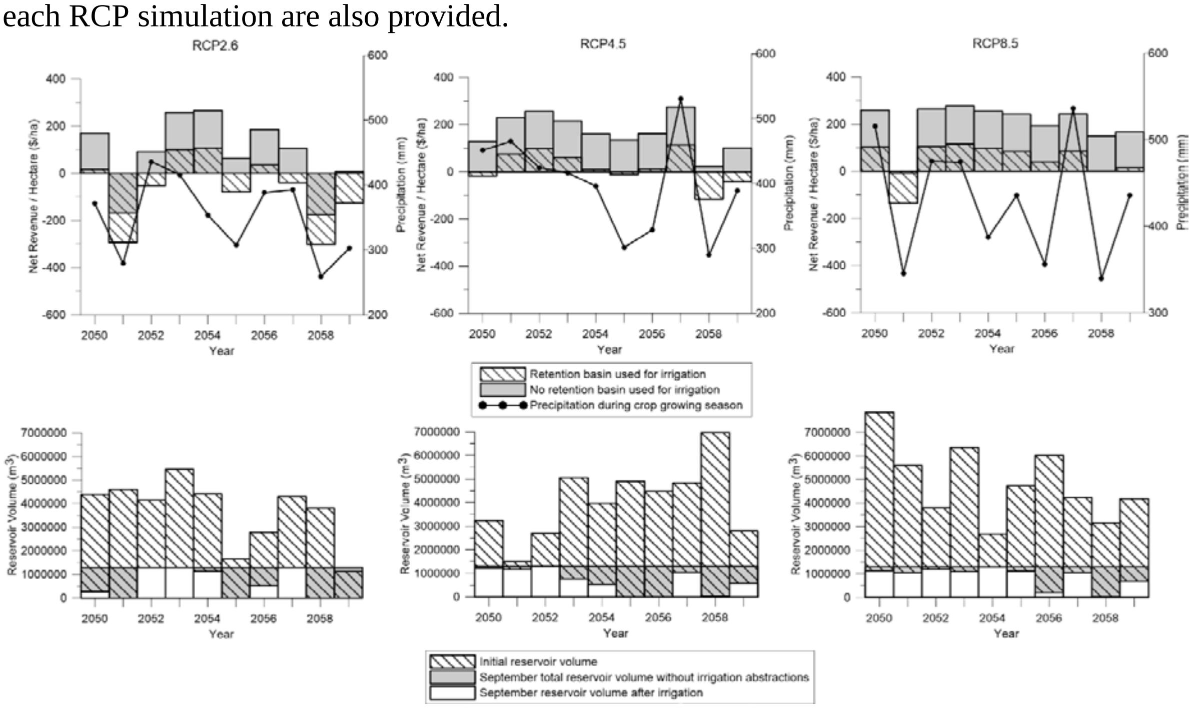

Figure A-2. Yearly 2050-2059 net crop revenue with and without irrigation application and yearly water availability for the GFDL-ESM2G climate model and each RCP. Reservoir levels from each RCP simulation are also provided.

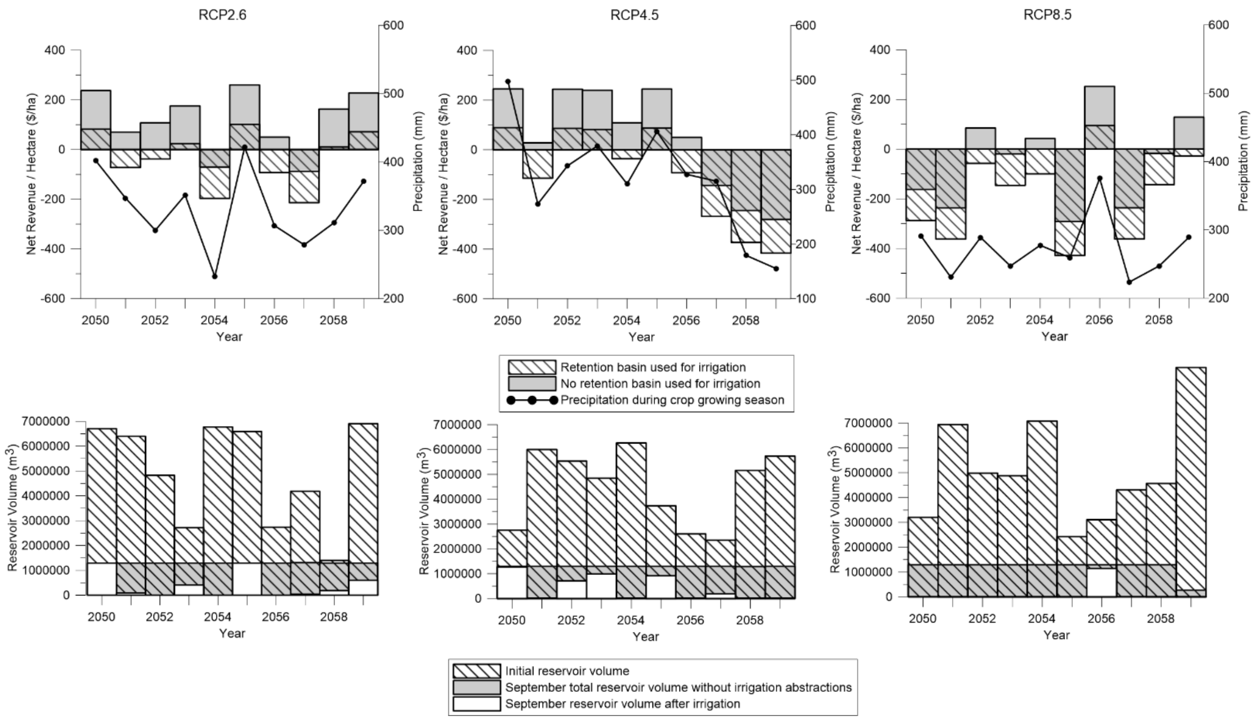

Figure A-3. Yearly 2050-2059 net crop revenue with and without irrigation application and yearly water availability for the HADGEM2 climate model and each RCP. Reservoir levels from each RCP simulation are also provided.

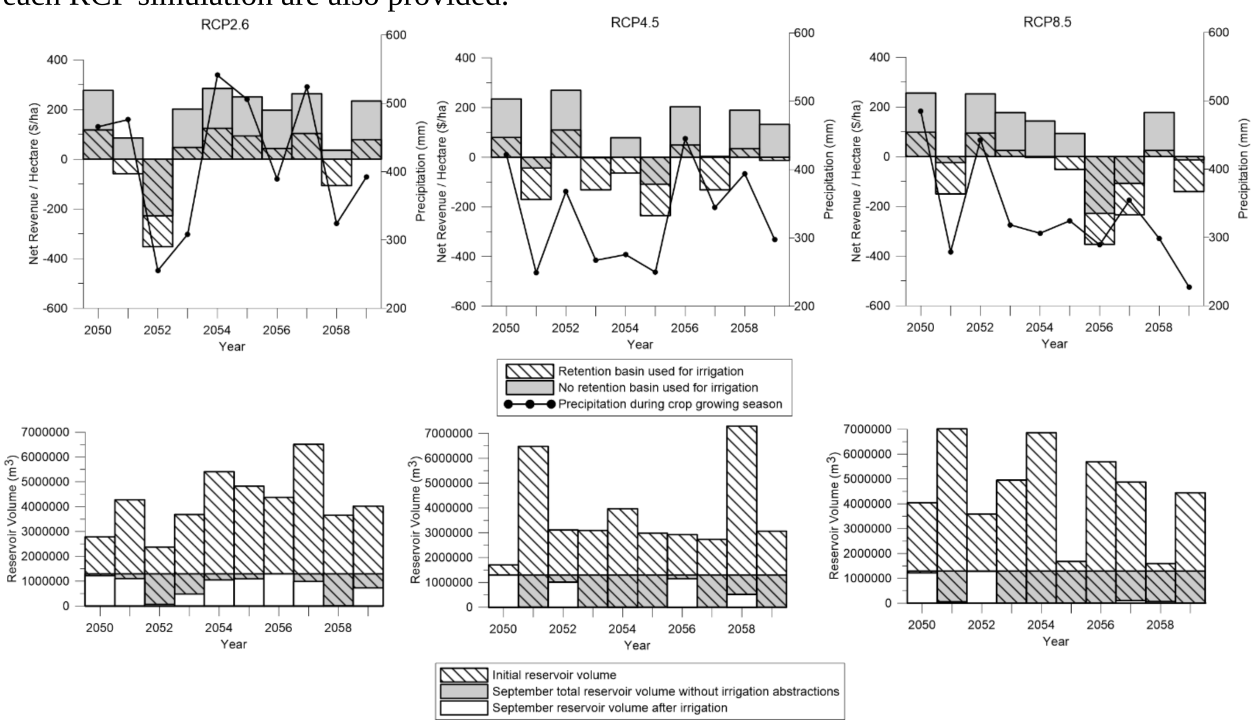

Figure A-4. Yearly net crop revenue with and without irrigation application and yearly water availability for the MPI-ESM-LR climate model and each RCP. Reservoir levels from each RCP simulation are also provided.

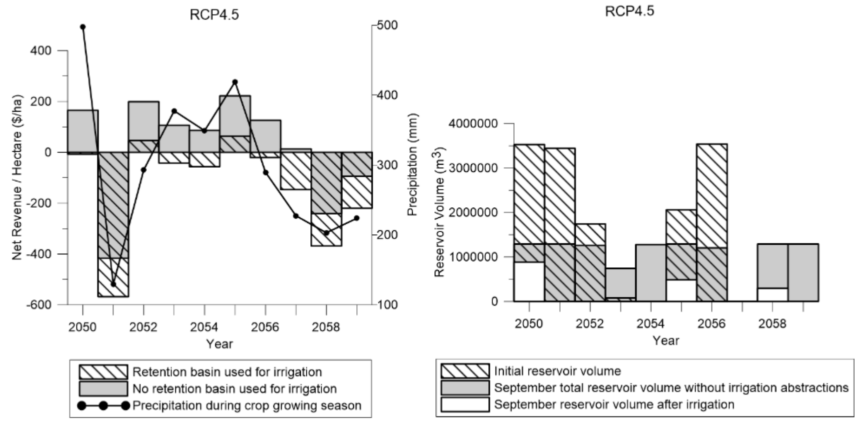

Figure A-5. Yearly 2050-2059 net crop revenue with and without irrigation application and yearly water availability using incremental precipitation and temperature increases in MESH for RCP4.5. Reservoir levels for RCP4.5 are also provided.

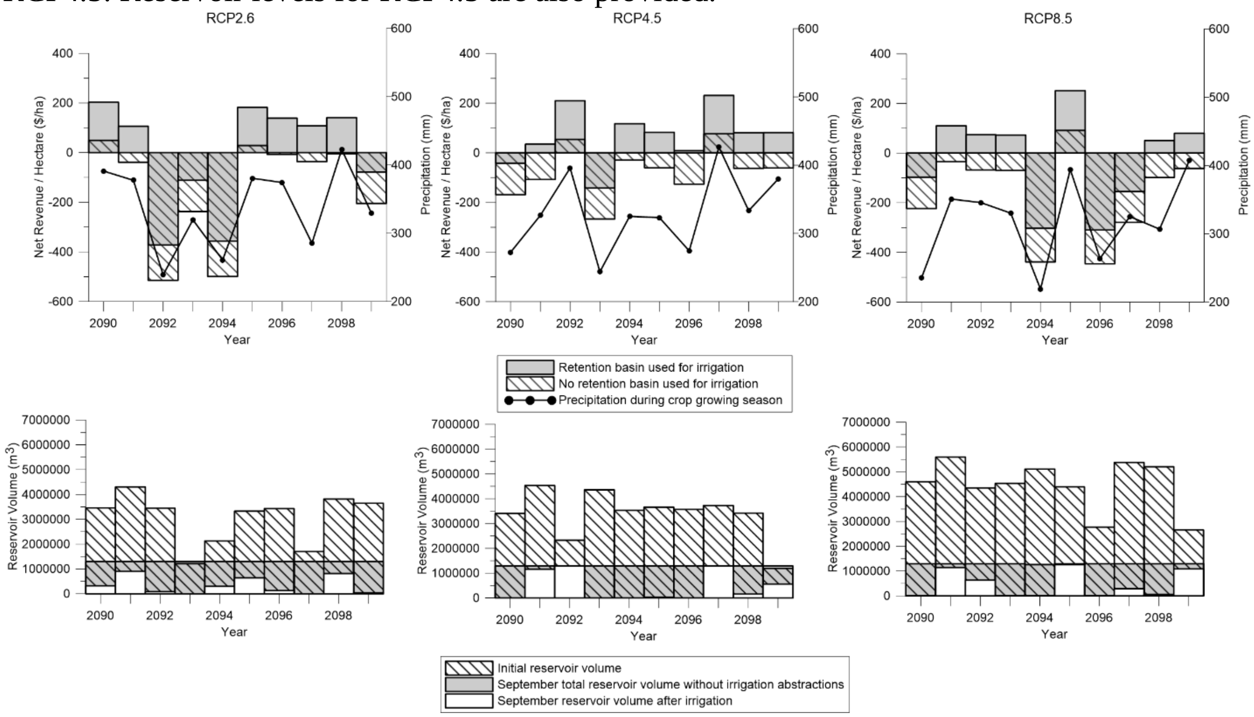

Figure A-6. Yearly 2090-2099 net crop revenue with and without irrigation application and yearly water availability for the CanESM2 climate model and each RCP. Reservoir levels from each RCP simulation are also provided.

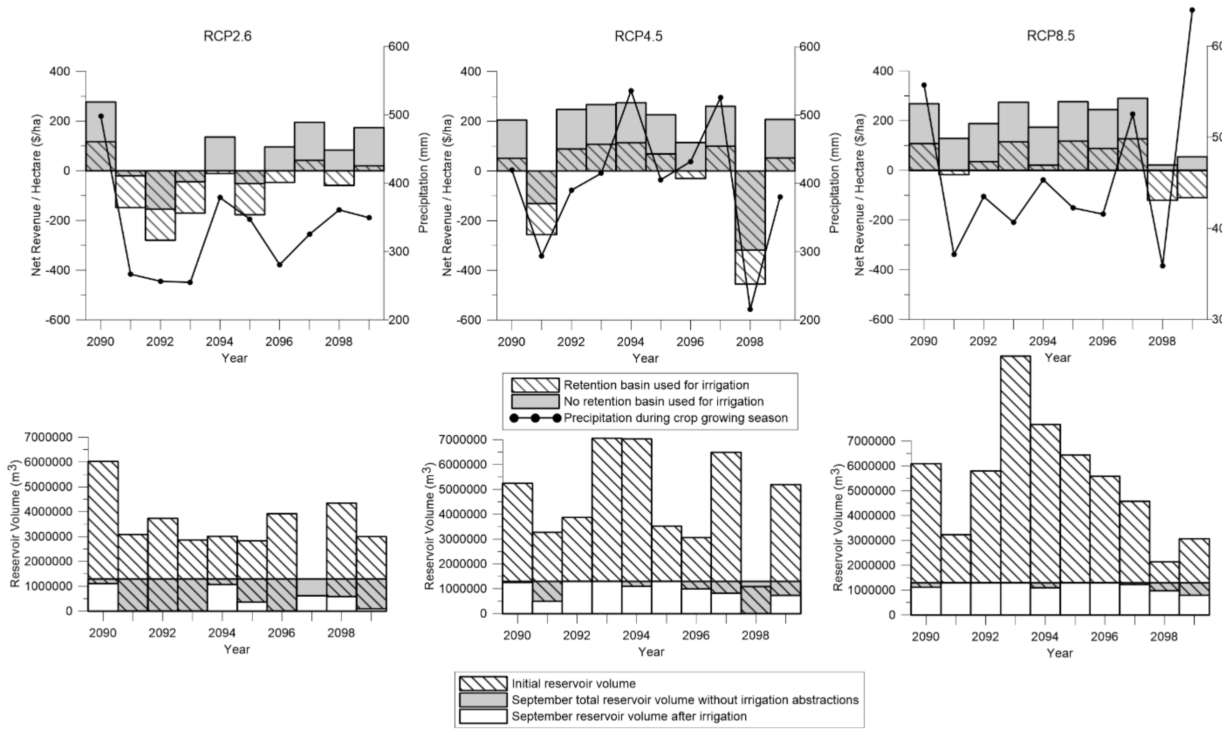

Figure A-7. Yearly 2090-2099 net crop revenue with and without irrigation application and yearly water availability for the GFDL-ESM2 climate model and each RCP. Reservoir levels from each RCP simulation are also provided.

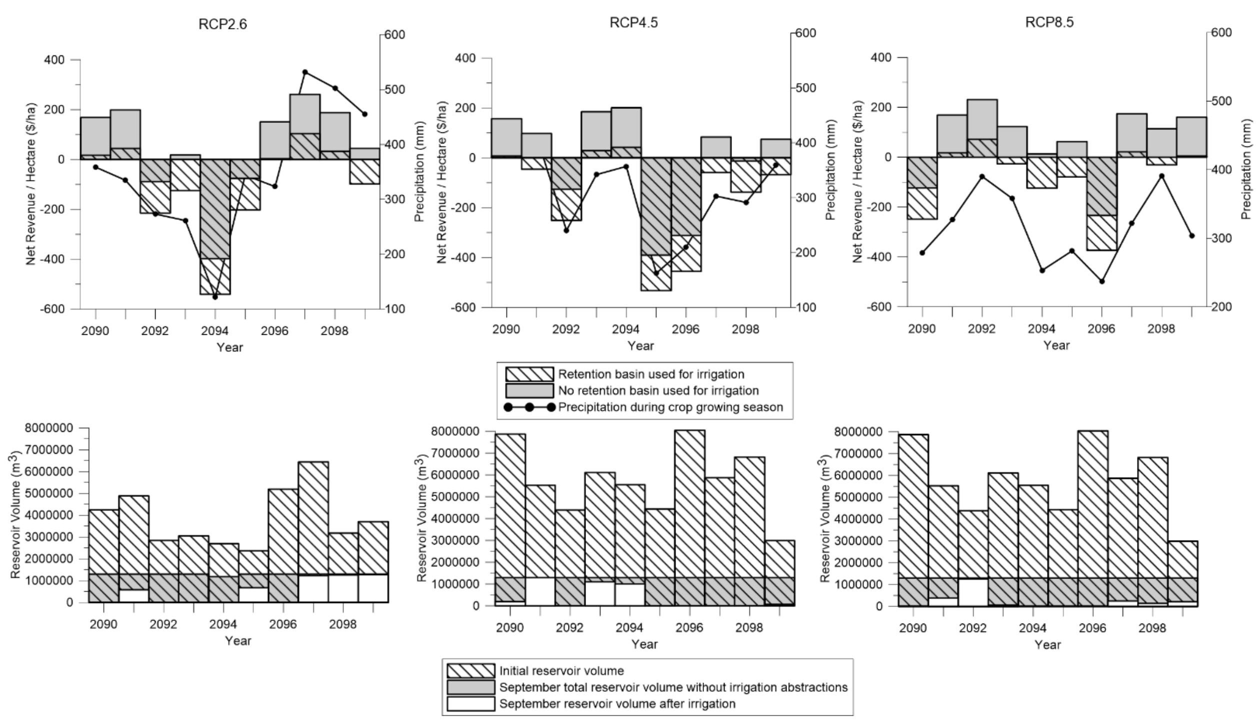

Figure A-8. Yearly 2090-2099 net crop revenue with and without irrigation application and yearly water availability for the HADGEM2 climate model and each RCP. Reservoir levels from each RCP simulation are also provided.

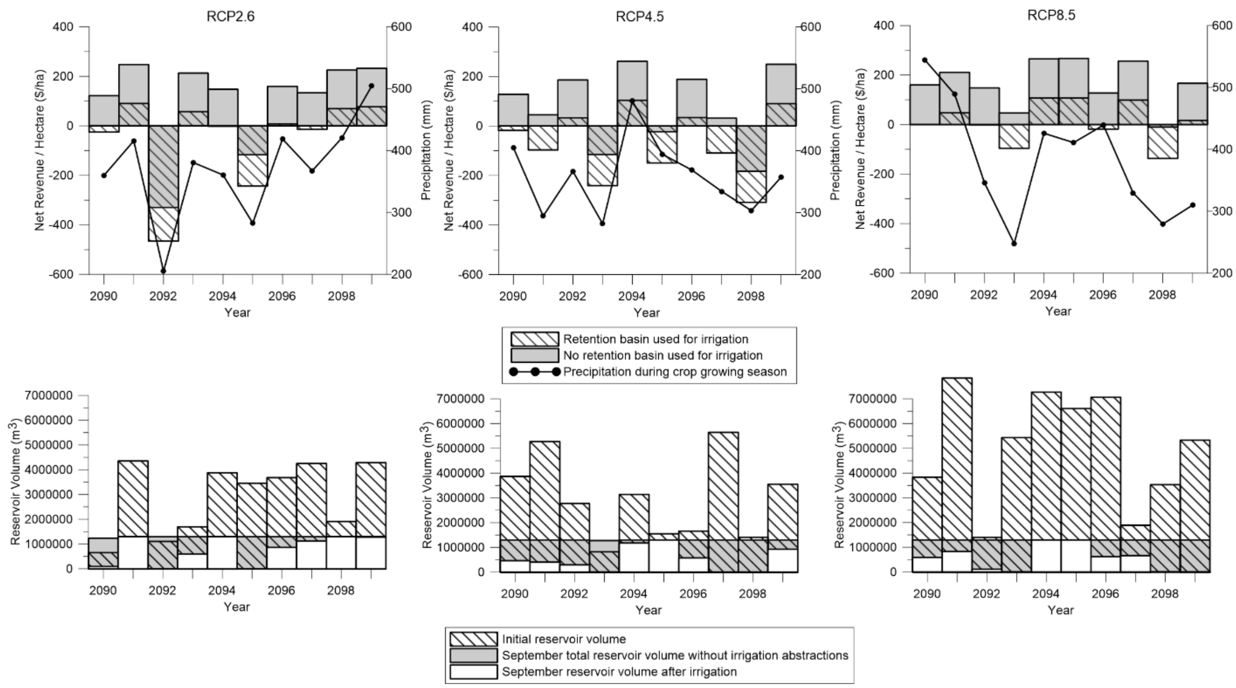

Figure A-9. Yearly 2090-2099 net crop revenue with and without irrigation application and yearly water availability for the MPI-ESM-LR climate model and each RCP. Reservoir levels from each RCP simulation are also provided.

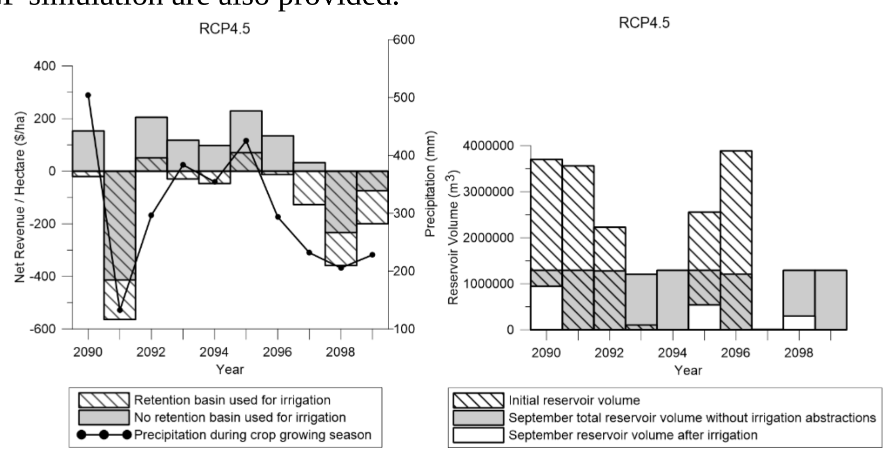

Figure A-10. Yearly 2090-2099 net crop revenue with and without irrigation application and yearly water availability using incremental precipitation and temperature increases for RCP4.5. Reservoir levels for RCP4.5 are also provided.